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A MANUAL

OF

STEAM-BOILERS:

THEIR

DESIGN, CONSTRUCTION, AND OPERATION.

FOR TECHNICAL SCHOOLS AND ENGINEERS.

BY

R. H. THURSTON, M.A., LL.D., DR. ENG'G;

Director of Sibley College, Cornell University; Past President American Society of Mechanical Engineers; Author of a "History of the Steam-engine," "Materials of Engineering," etc., etc., etc.

FOURTH EDITION.

NEW YORK:
JOHN WILEY AND SONS,
53 EAST TENTH STREET.
1892.

Electrotyped by
Drummond & Neu,
444 & 446 Pearl Street,
New York.

Printed by
Ferris Bros.,
326 Pearl Street,
New York.

PREFACE.

THE following treatise on the steam-boiler, its design, construction, and operation, is the outcome of an attempt to meet a demand which has been repeatedly made for a fairly complete, systematic, and scientific, yet "practical," manual. It has been intended to work to a plan that should be sufficiently comprehensive to meet the wants of the engineer in his office, and yet so rigidly systematic as to be suitable for use as a text-book in schools of engineering. It has been the endeavor to incorporate the elements of the subject just so far as they are needed in preparing the way for the work of the designer, the builder, and the manager of steam-boilers; while also amply complete and logical to permit the use of the book in the instruction of the student in applied science. It was not expected that it would be found practicable to make a manual of this kind absolutely complete as a workshop treatise to be used by the boiler-maker—a trade manual; but it was hoped that it might, within these limits, be made fairly satisfactory to the engineer engaged in designing.

The plan of the work is as follows: Beginning with an historical and descriptive introduction, in which are traced the various developments of the apparatus used by the engineers of the time of Watt and earlier, and by his successors, and the progress made since his time to date, the existing standard forms of boiler are described and classified, and their special adaptations indicated. A chapter is devoted to the study of the characteristics of the materials used by the engineer in the construction of steam-generators, and another to the strength of these metals in their several forms and compositions, the methods of adaptation to the purposes of construction, and to

the statement of the precautions to be observed in their introduction into so important a structure. Another chapter is appropriated to the examination of the composition and relative values of the various available fuels, and their economical use in the production of steam. These chapters on the materials and their characteristics are adapted mainly from the notes of lectures from which the larger work of the Author—"Materials of Engineering"—was compiled. It has been the endeavor of the Author to make this introductory portion of the book exceptionally complete, as it is the foundation of all that follows, and is a branch of the subject to which much attention is rarely given in treatises of this character. Following this part of the work are chapters upon the laws of thermodynamics, so far as they find application in the subsequent portion of the work, as, for example, in the determination of the magnitude of the stock of heat-energy stored in steam, and in the calculation of the constants required in tabulation of its properties; and this part of the scheme is introductory to a study of the properties of water in its several characteristic forms,—solid, liquid, gaseous,—and especially of the essential attributes of steam at the pressures and temperatures which are customarily met with in every-day practice. The tables, however, which are here given are carried up to a range of pressure and of temperature far exceeding those in common use, and it is thought are sufficiently complete to serve their purpose for many years, notwithstanding the unintermitted progress in the direction of higher pressures which is now observed, and which is not likely soon to completely cease. In these tables the constants of Rankine are adopted, not so much because it is considered by the Author, if we may judge from what is to-day known on this subject, that they are quite as likely to be correct as any others; but for the reason that they have become so generally accepted among engineers, and differ so little from the best values taken by earlier authorities, that it is probably wisest and safest to retain them—at least until the exact quantities are better settled than to-day. It is certain that the differences in the magnitudes now taken for the heat-equivalent, for example, and between those values

and the exact figures, are too small to be of moment to the engineer in the daily operations of professional work. Rankine's reconstruction of Regnault's results are here accepted, also; and Buel's tables, the only tables known to the Author in which this correction has been applied, are, with the consent of their author and his publishers, here given. The tables of Porter, published in his treatise on the Richards Steam-engine Indicator, may be used where separate tables in convenient and compact form are desired. The differences to be noted between the latter, which are compiled, with careful revision, directly from Regnault, and those of Rankine are not great; but the engineer should use either the one or the other exclusively in any one piece of work.

In the study of the methods and principles of designing steam-boilers, an attempt is made to collate the most essential, and to apply them to the proportioning of the best forms of boilers now familiar to the engineer. This part of the work is of great importance to the designing engineer, and it has been the endeavor to give this treatment of it a shape that will prove at once sufficient for its purpose, and yet fairly concise and very definite. It includes chapters on the design of the chimney and other accessories, and on specifications and contracts—subjects rarely touched upon in earlier manuals. The chapters on the operation and care of boilers, and their management generally, is largely based upon a somewhat extensive personal experience during earlier life, on the part of the Author, when he was engaged, first in the business of constuction, and later in actual practice, during the civil war, as a member of the corps of U. S. Naval Engineers, as well as during two decades of desultory practice as a consulting engineer since that time. It is hoped that it may prove well suited to meet the needs of the class of young men to whom it is addressed.

In the chapter on trials of steam-boilers, the methods reported favorably to the American Society of Mechanical Engineers are adopted as standard, and the report of the committee is taken almost bodily into the text. As this report, in part, was prepared by the Author from his lecture-notes

largely, and in consultation with the several distinguished engineers associated with him on that committee, it may, very probably, be admitted that this wholesale quotation is fully justified. The report will be found published in full in the Transactions of that Society, together with the discussion brought out by its presentation.

The chapter on explosions is already in print, with a few additions, as a treatise on the subject, published by Messrs. J. Wiley & Son. It was considered that such publication would very possibly prove of some service in preventing this probably absolutely preventable class of disasters, and that it would secure a wider circulation, and do so much the more good, if printed as a separate monograph.

The work, as a whole, is a larger treatise than could be used profitably in the average technical school; but it is thought that it may find its place in the special schools of mechanical engineering, in those which are properly entitled to be called professional schools, giving a training which really fits the student who may succeed in passing through them for entrance into the ranks of a profession which demands of its cadets a more complete preparation and a higher standing than any other, even among the distinctively so-called learned professions. The Author is fully conscious of the vast discrepancy between his aim and his accomplishment; but he hopes that the book may be of some service, nevertheless, to many engineers, old and young.

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THE STEAM-BOILER.

CHAPTER I.

HISTORY OF THE STEAM-BOILER—ITS STRUCTURE.

1. **The Office of a Steam-boiler** is to transfer the heat-energy produced by the combustion of fuel to the mass of enclosed water, and, by the conversion of the latter into steam, to store that energy in available form for use, as in the steam-engine.

The source of this energy was, originally, that existing in the rays of the sun, and, by the action of chemical affinity as exhibited in the growth of vegetation, it has been transformed from its kinetic form, in heat and light rays, to the potential form, as now found in the recent or fossil fuels of forest and coal-bed.

The process of absorption and storage of heat-energy in vegetable matter is reversed, in the furnace, in the combustion of the fuel; and the combination of the carbon and hydrogen, constituting the familiar hydrocarbons, with the oxygen of the air entering the "firebox," retransforms their stored, potential, energy into the available, kinetic, form of heat-motion, and it is then applied to the elevation of the temperature of the gaseous products of combustion and of the nitrogen passing through the boiler. By conduction and convection, and by radiation, in part, this heat is next transferred to the water in the boiler, raising its temperature, evaporating it, and "making steam" at a temperature fixed by the pressure under which the operation is carried on. By the formation of steam, a part of the heat is converted once more into the potential form by that method of performance of "internal work" in the separation of molecule from molecule, against the resistances due to cohesive forces, which measures the "latent heats" of evaporation and of

expansion; while the remainder is the sensible heat of the steam. Thus the fluid stored in the steam-boiler is a reservoir of energy which is drawn upon by the steam-engine when the latter is set in operation to transform that heat-energy into mechanical energy; and the steam sent from the boiler to the engine conveys to the latter this energy in the two forms of sensible and of latent heat, or of actual and potential energy.

The steam-boiler should be capable of thus producing, storing, and delivering heat-energy, in maximum quantity, and with maximum economy and safety. In other words, the steam-boiler should produce steam in the largest practicable quantity, with the least possible expenditure of fuel and of money, and with perfect safety.

2. **The Development of the Standard Forms of Steam-boiler** has been a process of trial and error, in some sense one of evolution of numerous types, and of the survival of the fittest, extending over many years. In the earlier days of the steam-engine the shapes assumed were invariably simple, and comparatively easy of construction. Thus the boiler shown by Hero (Fig. 1), in his "Pneumatica," two thousand years ago, was spherical; as were those of many later engines, all being evidently expected to be capable of sustaining considerable pressures.*

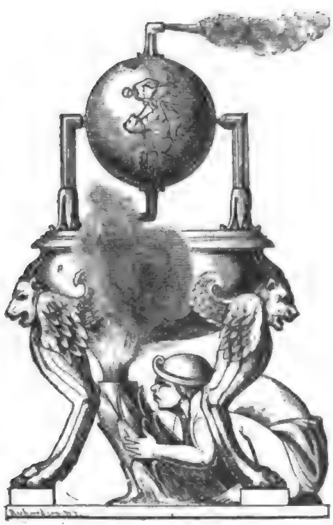

FIG. 1.—THE GRECIAN IDEA OF THE STEAM-ENGINE.

Thus, in 1601, Giovanni Battista della Porta, in his work "Spiritali," described an apparatus by which the pressure of steam might be made to raise a column of water, and the method of operation included the application of the condensation of steam to the production of a

* History of the Steam-engine. R. H. Thurston.

vacuum into which the water would flow. He used a separate boiler. Fig. 2 is copied from an illustration in a later edition of his work.*

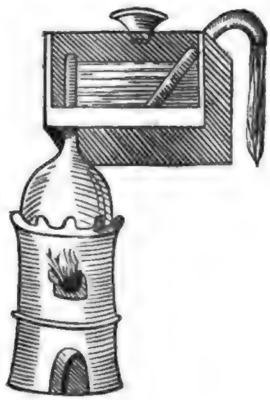

FIG. 2.—PORTA'S APPARATUS, A.D. 1601.

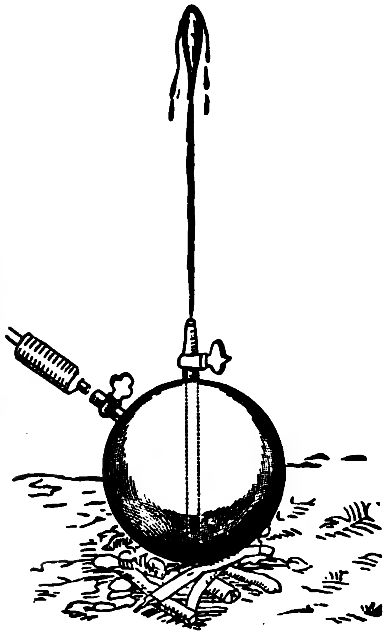

FIG. 3.—DE CAUS'S APPARATUS, A.D. 1615.

Again, in 1615, Salmon de Caus, who had been an engineer and architect under Louis XIII. of France, and later in the employ of the British Prince of Wales, published a work at Frankfort, entitled "Les Raisons des Forces Mouvantes avec diverses machines tant utile que plaisantes," in which he illustrated his proposition, "Water will, by the aid of fire, mount higher than its level," by describing a machine designed to raise water by the expanding power of steam. (See Fig. 3.) This consisted of a metal vessel partly filled with water, and in which a pipe was fitted leading nearly to the bottom and open at the top. Fire being applied, the steam, formed by its

* I Tre Libri Spiritali. Napoli, 1606.

elastic force, drove the water out through the vertical pipe, raising it to a height depending upon either the wish of the builder or the strength of the vessel.

In Worcester's apparatus, also (Fig. 4), we have a hardly less simple form of boiler, the operation of which is such as to render it subject to high pressure.

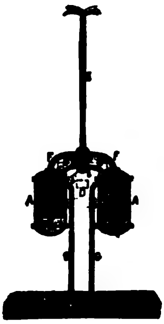

FIG. 4.—WORCESTER'S ENGINE, A.D. 1650.

Steam is generated in the boiler *D*, and thence is led into the vessel *A*, already nearly filled with water. It drives the water in a jet out through a pipe, *F* or *F'*. The vessel *A* is then shut off from the boiler and again filled "by suction" after the steam has condensed through the pipe *G*, and the operation is repeated, the vessel *B* being used alternately with *A*.

The *separate boiler*, as here used, constitutes a very important improvement upon the preceding forms of apparatus, although the idea was original with Porta.

Denys Papin, contemporary with the Marquis of Worcester, and a distinguished man of science of that time, invented the common lever safety-valve, and applied it to his "digester," as his closed vessel for cooking under pressure was called; he used it later (1690) on the steam-boilers connected with his own steam-engine. It has been continuously in use ever since.

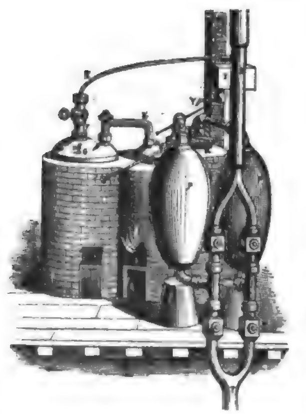

FIG. 5.—SAVERY'S ENGINE, A.D. 1699.

3. Forms familiar in the Last Century approximate modern types. Thomas Savery, A.D. 1699, used ellipsoidal forms in his then "newly invented fire-engine," of which Fig. 5 is a good representation, as first given by the inventor himself, in the "Miner's Friend."

L L is the boiler, in which steam is raised, and through the pipes *O O* it is alternately let into the vessels *P P*.

Suppose it to pass into the left-hand vessel first. The

valve *M* being closed and *r* being opened, the water contained in *P* is driven out and up the pipe *S* to the desired height, where it is discharged.

The valve *r* is then closed, and also the valve in the pipe *O*. The valve *M* is next opened, and condensing water is turned upon the exterior of *P* by the cock *Y*, leading water from the cistern *X*. As the steam contained in *P* is condensed, forming a vacuum, a fresh charge of water is driven by atmospheric pressure up the pipe *T*.

Meantime, steam from the boiler has been let into the right-hand vessel *P*, the cock *W* having been first closed and *R* opened. The charge of water is driven out through the lower pipe and the cock *R*, and up the pipe *S* as before, while the other vessel is refilling preparatory to acting in its turn.

The two vessels thus are alternately charged and discharged as long as is necessary. Savery's method of supplying his boiler with water was at once simple and ingenious.

The small boiler *D* is filled with water from any convenient source, as from the stand-pipe *S*. A fire is then built under it, and, when the pressure of steam in *D* becomes greater than in the main boiler *L*, a communication is opened between their lower ends and the water passes under pressure from the smaller to the larger boiler, which is thus "fed" without interrupting the work. *G* and *N* are *gauge-cocks* by which the height of water in the boilers is determined, and these attachments were first adopted by Savery.

It will be noticed that Savery, like the Marquis of Worcester, and like Porta, used a boiler separate from the water-reservoir.

A working model was submitted to the Royal Society of London in 1699,* and successful experiments were made with it.

Newcomen's engine, of 1705 and later, superseded the Savery apparatus in consequence of his adaptation of his machine to the use of low (atmospheric) pressure steam, quite as much as because of its greater economy. By introducing the

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* Transactions of the Royal Society, 1699.

beam-engine, and pumps separate from the steam-vessel, he was able to avoid all danger of explosion, using his steam at a pressure but little exceeding that of the atmosphere, and applying it simply to the displacement of the air, preliminary to the production of a vacuum. It thus became safe to use any convenient form of steam-vessel, and in Fig. 6 it is seen that he at once departed most signally from those shapes which had necessarily been earlier used, and took advantage of this freedom in design to secure a type of boiler of greater proportional area of heating-surface, as shown at *d*, and consequently of greater economy in use of fuel. It is seen that he used gauge-cocks, *c c*, and safety-valves, *N*.

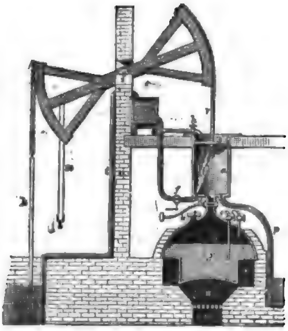

FIG. 6.—NEWCOMEN'S ENGINE AND BOILER, A.D. 1705.

James Watt's first boiler illustrates another step in this latter direction.

In this, *A*, Fig. 7, the "wagon-boiler," as he called it, the

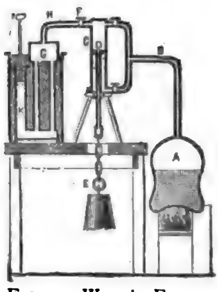

FIG. 7.—WATT'S FIRST MODEL, 1765.

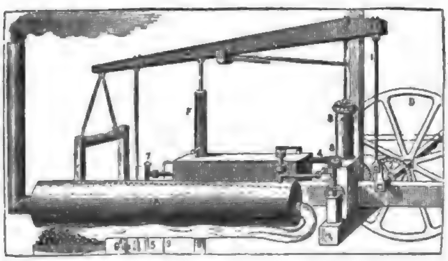

FIG. 8.—OLIVER EVANS'S ENGINE, 1800.

vessel is so shaped as to permit flues to be formed on either side, as well as below, for the circulation of the products of combustion backward and forward from end to end of the boiler.

A still further advance is illustrated in the now well-known "Cornish Boiler," Fig. 8, as used by Oliver Evans in the United States, and by British engineers of his time (1800), of which

the "shell" is cylindrical, and through which a single flue, of about one half the diameter of the boiler, passes from one end to the other. The gases traverse this flue and also partly envelop the exterior of the shell, thus coming in contact with a comparatively large extent of heating-surface. This form was followed by the "two-flued" Evans or Lancashire boiler, which was a cylinder containing two flues, each about one third its diameter, and by others in which the number of flues was increased with continually decreasing diameter, and with constant gain in total heating-surface until the modern types of tubular boiler were developed.

4. **Special Purposes produce the Modern Types** of boilers. Thus a desire to secure maximum efficiency produced the tubular boilers, and the desire to secure safety the so-called "sectional boilers." As early as 1793, Barlow invented, and

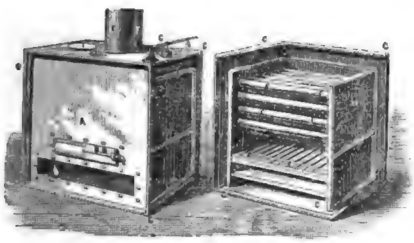

Fig. 9.—Water-tube Boiler of Fulton and Barlow, 1793.

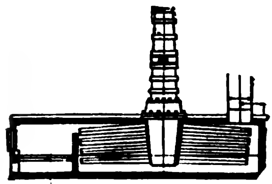

Fig. 10.—Stevens's "Sectional" Boiler, 1804.

with Fulton used, the "water-tube" boiler (Fig. 9), in which the water circulates through the tubes, instead of around them, as in "fire-tube" boilers. This was the pioneer of a great variety of boilers of this class.

John Stevens, a distinguished statesman as well as engineer, of the early part of the nineteenth century, devised another example of this class, shown in Fig. 10, as early as the year 1804.

The inventor says in his specifications: "The principle of this invention consists of forming a boiler by means of a system or combination of small vessels, instead of using, as is the common mode, one large one; the relative strength of the materials of which these vessels are composed increasing in proportion to the diminution of capacity." The steamboat boiler of 1804 was

built to bear a working pressure of over fifty pounds to the square inch, at a time when the usual pressures were from four to seven pounds. It consists of two sets of tubes, closed at one end by solid plugs, and at their opposite extremities screwed into a stayed water and steam reservoir, which was strengthened by hoops. The whole of the lower portion was inclosed in a jacket of iron lined with non-conducting material. The fire

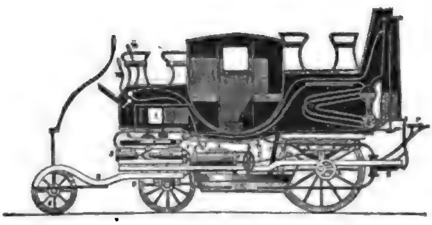

FIG. 11.—GURNEY'S STEAM-CARRIAGE, 1833.

was built at one end, in a furnace inclosed in this jacket. The furnace-gases passed among the tubes, down under the body of the boiler, up among the opposite set of tubes, and thence to the smoke-pipe. In another form, as applied to a locomotive in 1825, the tubes were set vertically in a double circle sur-

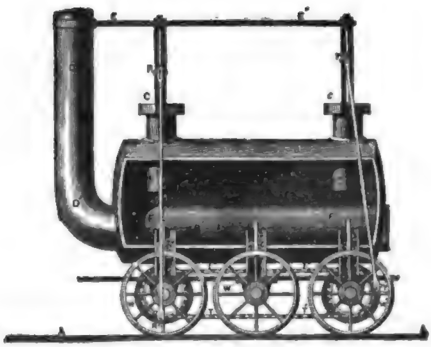

FIG. 12.—STEPHENSON'S LOCOMOTIVE, 1815.

rounding the fire. These boilers are carefully preserved among the collections of the Stevens Institute of Technology.

Still another modification of this type is illustrated in the boiler used by Gurney in steam-carriages (Fig. 11) built about the years 1830–5, in which the steam-generator consisted of bent steam-pipe of small diameter so connected with steam and mud

drums as to make a very efficient as well as safe and powerful boiler for use where lightness, strength, and safety were essential characteristics.

Similarly, the special demands of locomotive construction were not fully met by the single-flue boiler first used by George Stephenson (Fig. 12) and by his colleagues in 1815, and up to

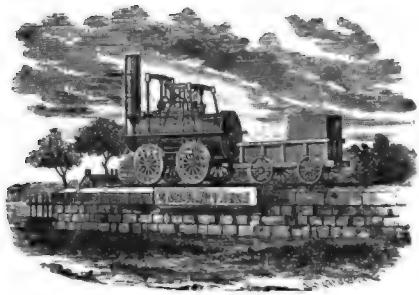

FIG. 13.—STOCKTON AND DARLINGTON ENGINE NO. 1, 1825.

the time of construction of the Stockton and Darlington Railway in 1825 (Fig. 13), an example of which is still preserved in the first engine built for that road. At the opening of the Liverpool and Manchester Railway (1829), Stephenson's Rocket was given the multitubular boiler, a form which had grown into shape in the hands of several inventors.* This boiler was three feet in diameter, six feet long, and had twenty-five three-inch tubes, extending from end to end of the boiler. The steam-blast was carefully adjusted by experiment, to give the best effect. Steam-pressure was carried at fifty pounds per square inch.

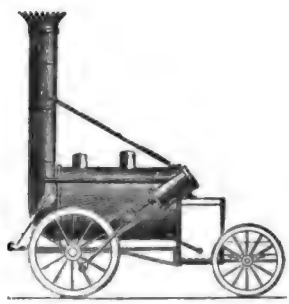

FIG. 14.—THE ROCKET, 1829.

The average speed of the Rocket on its trial was fifteen miles per hour, and its maximum was nearly double that—twenty-nine miles an hour; and afterward, running alone, it reached a speed of thirty-five miles.

* Barlow and Fulton, 1795; Nathan Read, Salem, United States, 1796; Booth of England, and Séguin of France, about 1827 or 1828.

The shares of the company immediately rose ten per cent in value. The combination of the non-condensing engine with a steam-blast and the multitubular boiler, designed by the clear head and constructed under the eye of an accomplished engineer and mechanic, made steam locomotion so evident and decided a success, that thenceforward its progress has been uninterrupted and wonderfully rapid.*

The special requirements of stationary steam-engine construction and operation, and of steam navigation, have, from these primitive types and forms, developed in the course of years the several now common and standard boilers which will be later described.

5. **The Method and Extent of Improvement** is now easily traced. Looking back over the history of the steam-engine, we may rapidly note the prominent points of improvement and the most striking changes of form; and we may thus obtain some idea of the general direction in which we are to look for further advance.†

Beginning with the machine of De Caus, at which point we may first take up an unbroken thread, it will be remembered that we there found a single vessel performing the functions of all the parts of a modern pumping-engine; it was at once boiler, steam-cylinder, and condenser, as well as both a lifting and a forcing pump. The Marquis of Worcester, and, still earlier, Da Porta, divided the engine into two parts; using one part as a steam-boiler, and the other as a separate water-vessel. Savery duplicated those parts of the earlier engine which acted the several parts of pump, steam-cylinder, and condenser, and added the use of the jet of water to effect rapid condensation. Newcomen and Cawley next introduced the modern type of engine, and separated the pump from the steam-engine proper; in their engine, as in Savery's, we notice the use of surface-condensation first, and, subsequently, that of a jet of water thrown into the midst of the steam to be condensed. Watt finally effected the crowning improvement of the single-cylinder

* History of the Steam-engine. R. H. Thurston. N. Y.: D. Appleton & Co., 1878.

† Ibid.

engine, and completed this movement of differentiation by separating the condenser from the steam-cylinder, thus perfecting the general structure of the engine.

Here this movement ceased, the several important processes of the steam-engine now being conducted each in a separate vessel. The boiler furnished the steam; the cylinder derived from it mechanical power; the vapor was finally condensed in a separate vessel; while the power, which had been obtained from it in the steam-cylinder, was transmitted through still other parts to the pumps, or wherever work was to be done.

Watt and his contemporaries also commenced that movement toward higher pressures of steam, used with greater expansion, which has been the most striking feature noticed in the progress made since his time. Newcomen used steam of barely more than atmospheric pressure, and raised 105,000 pounds of water one foot high, with a pound of coal consumed. Smeaton raised the steam-pressure to eight pounds, and increased the duty to 120,000. Watt started with a duty of double that of Newcomen, and raised it 320,000 foot-pounds per pound of coal, with steam at ten pounds. To-day, Cornish engines of the same general plan as those of Watt, but worked with forty to sixty pounds pressure, expanding three to six times, bring up the duty to 600,000 foot-pounds; while more modern compound engines have boilers carrying 150 pounds (ten atmospheres) above the normal air-pressure, and the duty has been since raised to above 1,200,000 foot-pounds per pound of fuel used.

6. The Requisites of Good Design are readily prescribed and defined: they are very simple, and although attempts are almost daily made to obtain improved results by varying the design and arrangement of heating-surface, the best boilers of nearly all makers of acknowledged standing are practically equal in merit, although of diverse forms.

In making boilers the effort of the engineer should evidently be—

1st. To secure complete combustion of the fuel without permitting dilution of the products of combustion by excess of air.

2d. To secure as high temperature of furnace as possible.

3d. To so arrange heating-surfaces that, without checking draught, the available heat shall be most completely taken up and utilized.

4th. To make the form of boiler such that it shall be constructed without mechanical difficulty or excessive expense.

5th. To give it such form that it shall be durable, under the action of the hot gases and of the corroding elements of the atmosphere.

6th. To make every part accessible for cleaning and repairs.

7th. To make every part as nearly as possible uniform in strength, and in liability to loss of strength by wear and tear, so that the boiler when old shall not be rendered useless by local defects.

8th. To adopt a reasonably high "factor of safety" in proportioning.

9th. To provide efficient safety-valves, steam-gauges, and other appurtenances.

10th. To secure intelligent and very careful management.

7. Effective Development, Transfer, and Storage of Heat, in the best possible combination, is evidently what is demanded in the operation of the steam-boiler.

In securing complete combustion an ample supply of air and its thorough intermixture with the combustible elements of the fuel are essential; for the second, high temperature of furnace, it is necessary that the air-supply shall not be in excess of that absolutely needed to give complete combustion. The efficiency of a furnace burning fuel completely is measured by

$$E = \frac{T - T'}{T - t},$$

in which E represents the ratio of heat utilized to the whole calorific value of the fuel; T is the furnace-temperature; T' the temperature of the chimney, and t that of the external air. Hence the higher the furnace-temperature and the lower that of the chimney, the greater the proportion of available heat.

It is further evident that, however perfect the combustion,

no heat can be utilized if either the temperature of chimney approximates to that of the furnace, or if the temperature of the furnace is reduced by dilution approximately to that of the chimney. Concentration of heat in the furnace is secured, in some cases, by special expedients, as by heating the entering air, or, as in the Siemens gas-furnace, heating both the combustible gases and the supporter of combustion. Detached fire-brick furnaces have an advantage over the "fireboxes" of steam-boilers in their higher temperature; surrounding the fire with non-conducting and highly heated surfaces is an effective method of securing more perfect combustion and high furnace-temperature.

In arranging heating-surface the effort should be to impede the draught as little as possible, and so to place them that the circulation of water within the boiler should be free and rapid at every part reached by the hot gases.

The directions of circulation of water on the one side and of gas on the other side the sheet should, whenever possible, be opposite. The cold water should enter where the cooled gases leave, and the steam should be taken off farthest from that point. The temperature of chimney-gases has thus been reduced by actual experiment to less than 300° Fahr., and an efficiency equal to 0.75 to 0.80 the theoretical is attainable.

The extent of heating-surface simply, in all of the best forms of boiler, determines the efficiency, and the disposition of that surface in such boilers seldom affects it to any great extent. The area of heating-surface may also be varied within wide limits without greatly modifying efficiency. A ratio of 25 to 1 in flue and 30 to 1 in tubular boilers represents the relative area of heating and grate surfaces in the practice of the best-known builders. This proportion may be often settled by exact calculation.

The material of the boiler, as will be shown later, should be tough and ductile iron, or, better, a soft steel containing only sufficient carbon to insure melting in the crucible or on the hearth of the melting-furnace, and so little that no danger may exist of hardening and cracking under the action of sudden and great changes of temperature.

Where iron is used it is necessary to select a somewhat hard but homogeneous and tough quality for the firebox sheets or any part exposed to flames.

The factor of safety is very often too low. The boiler should be built strong enough to bear a pressure at least six times the proposed working-pressure; as the boiler grows weak with age, it should be occasionally tested to a pressure far above the working-pressure, which latter should be reduced gradually to keep within the bounds of safety. The factor of safety is seldom more than four in new boilers; and even this is reduced practically by the operation of the inspection laws.

Effective development of heat is secured primarily by the selection of good fuel, by which is usually meant fuel which consists, to the greatest possible extent, of available combustible material; but for the purposes of the engineer who designs the boiler, or of the owner for whom it is to be constructed, the real criterion of quality is the quantity of heat which the combustible, as burned in the furnace, will yield for any given sum of money expended in obtaining that heat. The cost of a fuel to the consumer consists, not simply of money paid for it to the dealer who supplies it, but also of cost of transportation and of placing in the grate, of removal of ash, of incidental expenses inseparable from its use, such as injury to boilers and other property, increased risks, and other such expenses, many if not most of which are very difficult of determination with any satisfactory decree of accuracy. Other things being equal, that fuel which gives the greatest quantity of available heat for the total money expenditure is that which permits most effective development in the sense here taken. Effective heat-development from any selected fuel is secured, as already stated, by its complete combustion in such manner as to give the highest possible temperature.

Effective transfer of heat is secured by such a form of steam-generator, and such extent and disposition of "heating-surfaces," as will most completely utilize the heat developed in the furnace and flues by causing it to flow, with the least possible loss, into the water and steam contained within the boiler; and this is effected by proper arrangement of surfaces absorb-

ing heat from the gases and yielding it to the liquid as already generally described.

Effective storage of heat can be secured by providing large volumes of water and of steam, within which the heat transferred from the furnace and flues can be stored, and by carefully protecting the whole heated system from waste by conduction or radiation to adjacent bodies. Where the demand is steady, and the supply from the fuel fairly steady also, the amount stored need not be great, as the use of the reservoir is simply that of a regulator between furnace and engine or other apparatus receiving it; but where either supply or demand is variable, considerable storage capacity may be needed.

8. **Efficient Utilization of Heat** is as essential to the satisfactory working of any system of generation and application of heat as is efficient production, transfer, and storage. The mode of attaining maximum efficiency depends upon the nature of the demand and the method of expenditure; and the consideration of this subject in detail would be here out of place. In general it may be said that where the heat and steam are required for the impulsion of an engine, the higher the safe pressure and the practically attainable temperature at which the supply is effected, the more efficient the utilization of the heat. These limits of temperature and pressure are the higher as the actual working conditions are made the more closely to approximate to the ideal conditions prescribed by pure science.

Where heating simply, without transformation into work, is intended, the principal and only very important requisite, usually, is to provide such thorough protection for the system of transfer and use, that no wastes of importance can take place by radiation or conduction. The character of the steam made, as to humidity, is in this case comparatively unimportant; but in the preceding case it will be found essential that it should be always dry, and it is often much the better for being superheated considerably above the boiling-point due to its pressure.

The actual standing of the best steam-engine of the present time, as an efficient heat-engine, is really very high. The sources of loss are principally quite apart from the principles of design and construction, and even from the operation of the

machine; and it may be readily shown that, to secure any really important advance toward theoretical efficiency, a radical change of our methods must be adopted, and probably that we must throw aside the heat-engine in all its forms, and substitute for it some other apparatus by which we may utilize some mode of motion and of natural energy other than heat.

The very best classes of modern steam-engines very seldom consume less than two pounds (0.9 kilog.) of coal per horse-power per hour, and it is a good engine that works regularly on three pounds (1.37 kilog.).

The first-class steam-engine, therefore, yields less than 10 per cent of the work stored up in good fuel, and the average engine probably utilizes less than 5 per cent. A part of this loss is unavoidable, being due to natural conditions beyond the control of human power, while another portion is, to a considerable extent, controllable by the engineer or by the engine-driver. Scientific research has shown that the proportion of heat stored up in any fluid, which may be utilized by perfect mechanism, must be represented by a fraction, the numerator of which is the range of temperature of the fluid while doing useful work, and the denominator of which is the temperature of the fluid when entering the machine, measured from the "absolute zero."

Thus, steam, at a temperature of 320° Fahr., being taken into a perfect steam-engine, and doing work there until it is thrown into the condenser at 100° Fahr., would yield $\frac{320 - 100}{320 + 461} = 0.28 +$, or rather more than one fourth of the work which it should have received from each pound of fuel. The proportion of work that a non-condensing but otherwise perfect engine, using steam of 75 pounds (5 atmos.) pressure, could utilize would be $\frac{320 - 212}{320 + 461} = 0.14 = \frac{1}{7}$; and, while the perfect condensing engine would consume two thirds of a pound (0.3 kilog.) of good coal per hour, the perfect non-condensing engine would use $1\frac{1}{3}$ pounds (0.6 kilog.) per hour for each horse-power developed, the steam being taken into the engine and exhausted at the temperatures assumed above.

Also, were it possible to work steam down to the absolute zero of temperature, the perfect engine would require but 0.19 pound (0.09 kilog.) of similar fuel.

It may therefore be stated, with a close approximation to exactness, that of all the heat derived from the fuel about seven tenths is lost through the existence of natural conditions over which man can probably never expect to obtain control, two tenths are lost through imperfections in our apparatus, and only one tenth is utilized in even good engines. Boiler and engine are intended to be included when writing of the steam-engine above. In this combination a waste of probably two tenths at least of the heat derived from the fuel takes place in the boiler and steam-pipes, on the average, in the best of practice, and we are therefore only able to anticipate a possible saving of $0.2 \times 0.75 = 0.15$, about one sixth of the fuel now expended in our best class of engines, by improvements in the machine itself. The best steam-engine, apart from its boiler, therefore, has 0.85, about five sixths, of the efficiency of a perfect engine, and the remaining sixth is lost through waste of heat by radiation and conduction externally, by condensation within the cylinder, and by friction and other useless work done within itself. It is to improvement in these points that inventors must turn their attention if they would improve upon the best modern practice by changes in construction.

To attain further economy, after having perfected the machine in these particulars, they must contrive to use a fluid which they may work through a wider range of temperature, as has been attempted in air-engines by raising the upper limit of temperature, and in binary vapor engines by reaching toward a lower limit, or by working a fluid from a higher temperature than is now done down to the lowest possible temperature. The upper limit is fixed by the heat-resisting power of our materials of construction, and the lower by the mean temperature of objects on the surface of earth, being much lower at some seasons than at others. In the boiler the endeavor must be made to take up all the heat of combustion, sending the gases into the chimney at as low a temperature as possible, and securing in the furnace perfect combustion without excess of

air-supply. The best engines still lack 15 per cent of perfection, and the best boilers, as an average, over 30 per cent.

9. **Safety in Operation** is one of the most essential requirements which the designer, constructor, and user of steam-boilers must be prepared to fulfil. As will be seen later, the quantity of stored heat-energy in the steam-boiler is usually enormous, and this energy is stored under such conditions that, if set free by the rupture of the containing vessel, wide-spread disaster may ensue. This stored energy is at all times ready to instantly assume the kinetic form when permitted, and by doing mechanical work on all adjacent objects, to produce most extraordinary effects; it is stored energy of the most perfectly elastic kind, as well as of high tension. The most absolutely reliable means known to the engineer must be adopted for the safe and permanent control of such magazines of latent power.

Those methods of securing safety which have been found most satisfactory have been—

(1) The division of the confined energy among comparatively small masses of steam and water contained in correspondingly small communicating chambers, so constructed that the rupture of one will be unlikely to produce fracture of any other.

(2) The adoption of the very best material and of the best possible construction, and so proportioning all parts exposed to stress and strain that they may withstand pressures several times as great as the maximum intended to be carried.

(3) Careful and intelligent operation and preservation.

10. **The Appurtenances or Accessories of Steam-boilers** are those attached parts and apparatus which, while not, strictly speaking, actually essential elements of the structure specially designated as the boiler, are nevertheless essential to its safe and economical operation: such as, for example, safety and other valves, gauge-cocks, feed-pumps, dampers, grates, and "settings."

Safety-valves are automatically self-operating apparatus which open and permit the steam to issue from the boiler whenever the pressure reaches a limit at which they are arranged to act. Steam-valves are the valves, usually operated by screws, which, when open, permit the steam to leave the boiler and pass away through the steam-pipes. Stop-valves are a

variety of valve which may be used to stop the passage of steam from the boiler: they may be "screw stop-valves," or simple valves moved directly by hand. Check-valves, commonly introduced at the junction of the feed-water supply-pipe with the boiler, are so arranged as to open automatically when the stream enters, but to close against a return current: they are sometimes pinned to their seats, when desirable, by a screw, in which case they are called "screw-checks." Gauge-cocks are set at, and above or below, the intended working water-level of the boiler, and, when opened, by discharging steam or water, indicate the actual position of the water-line. Glass water-gauges are glass tubes set in such manner that the water stands in a vertical tube at the same height as the water in the boiler, the top of the glass communicating with the steam-space, and the lower end with the water-space of the boiler.

11. The Classification of Steam-boilers may be based upon either a comparison of their forms or of their purpose. Under the former we have the plain cylindrical, the flue, the tubular, or the sectional boiler; under the latter, stationary, locomotive, or marine boilers. For the purposes of this work, the following may be taken as a satisfactory scheme:

Stationary . . .	Plain cylindrical boilers.	
	Cornish or single-flue.	
	Lancashire or two-flue.	
	Multiflue and return-flue boilers.	
	Cylindrical fire-tube boilers.	
	Firebox boilers.	
	Sectional boilers.	
	Peculiar forms.	
Locomotive . . .	Common type.	
	Wooton boilers.	
	Special devices.	
Marine	Older types	Flue.
		Flue and tube.
		Tubular.
	Scotch or drum boilers.	
	Water-tube and sectional.	
	Miscellaneous forms.	

12. The Modern Standard Types of Boiler are becoming rapidly settled in a few well-defined forms which have been found to be most satisfactory, all things considered, each in its own special province. These are specified in the list just presented. But many boilers have become so thoroughly well adapted to the special work to which they are customarily applied as to have almost or quite entirely displaced other forms, which in turn are as generally adopted for other uses. Thus, where the feed-water supplied to land boilers, in localities where fuel is cheap, or water bad, and certain to produce serious incrustation, the plain cylindrical boiler is almost universally employed; where the fuel is costly and the feed-water pure, the tubular boiler is as universally adopted; while intermediate conditions lead to the use of intermediate forms. The locomotive boiler is standard for its place and purpose, and no other form has ever yet competed with it in thorough adaptation to that peculiar case. The high pressures carried and the necessity of great economy at sea have made the so-called "Scotch" or "drum" boiler standard in trans-oceanic steam navigation. Where small area of floor-space and ample "head-room" are found, the upright cylindrical tubular boiler is the standard form; if the head-room is less and the floor-space larger, a modification of the locomotive type finds application for stationary purposes.

13. Mixed Types of boiler are often constructed for special purposes or experimentally. In the shallow-water navigation of the United States of America, as on the Hudson River, the flue and tube boiler is much used; the locomotive type of boiler, with fewer and larger tubes than are adopted in locomotive practice, has often found use in stationary practice. New designs are continually coming forward which illustrate such forms of boiler. As a rule, however, they are not found preferable to the simpler and standard types.

14. Mixed Applications are sometimes required, as where the same boiler supplies steam for power and for heating purposes. In this case the pressure carried on the boiler is fixed at the proposed maximum for the engine, and the lower pressures required for the other purpose are secured by the use

of a "reducing" or "pressure-reducing" valve. The steam-heating systems of cities often illustrate this case, furnishing steam, as they do, for heating buildings, for cooking, and to steam-engines at all parts of the area covered by them.

15. Common Forms of "Shell" Boilers, as those boilers are called in which the structure consists of an external case enclosing steam and water, flues and tubes, are the following:

(1) *The Plain Cylindrical Boiler* consists, as shown in section (Fig. 15), and in front elevation (Fig. 16), of a simple cylin-

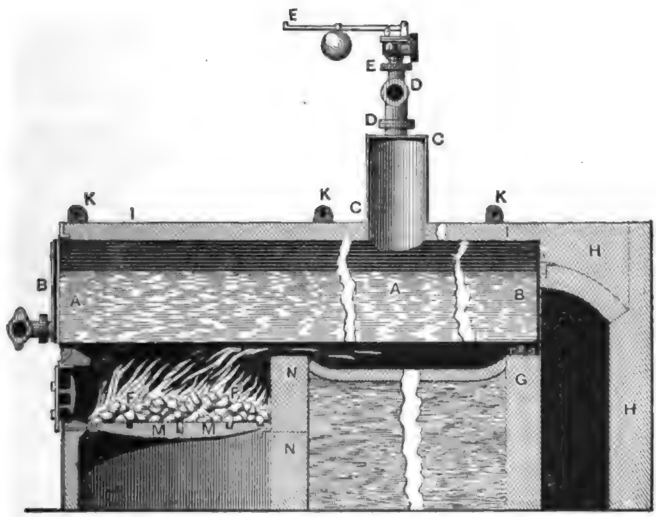

FIG. 15.—SECTION OF CYLINDRICAL BOILER.

drical vessel, *A*, made of boiler-plate, fitted with heads at each end, *B*, *B*; which heads are sometimes of sheet-iron and sometimes of cast-iron. A steam-dome, *C*, on the upper side, usually serves as a collector and reservoir for the steam, as it rises from the water into the steam-space, and serves also as the point of attachment for the steam-pipe, *D D*, and safety-valve, *E E*, both of which thus take steam from the highest and driest part of the interior of the boiler.

The fire is built in the detached furnace, *F F*, the products of combustion passing under the boiler to the rear, at *G*, where

a flue leads off to the chimney. The "setting" consists of side-walls and ends, *H H*, of brick, and a covering, *I I*, which is often merely a filling of ashes or other non-conductor, or an arch of brickwork carried over from the side-walls. "Binders," *K K*, and rods, *L L*, tie the whole together, and resist any change of form due to variations of temperature. The grates,

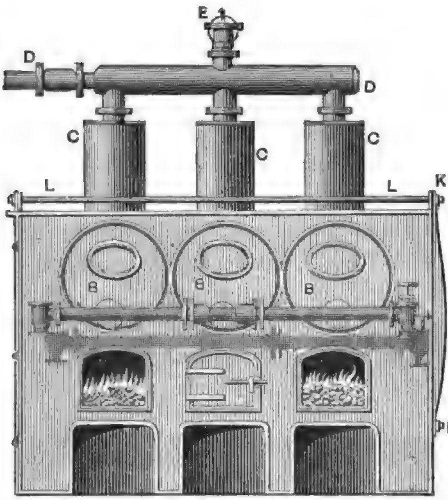

FIG. 16.—FRONT OF CYLINDRICAL BOILER AND SETTING.

M M, are supported at the rear by the bridge-wall, *N N*, of which the upper part is usually built of fire-brick. The rear end of the boiler is often carried on rollers, to prevent danger of injury with the changes of form due to variations of temperature such as are produced by the introduction of cold feed-water.

(2) *The Cylindrical Flue Boiler* (Fig. 17) is a plain cylinder, like the preceding form, but with one or more flues passing through it from end to end. The setting is usually quite similar to that of the plain cylinder, except as necessarily modified to meet the requirements of the flue. The shell is generally shorter than that of the first-described boiler, the heating-surface considerably greater.

(3) *The Cylindrical Tubular Boiler* is shown in one of the best forms in Fig. 18. It consists of a cylindrical shell con-

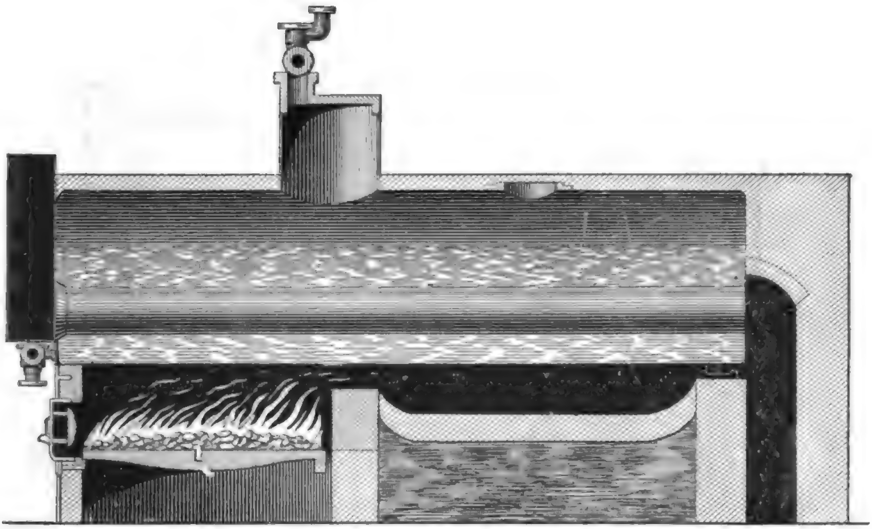

FIG. 17.—CYLINDRICAL FLUE BOILER.

structed much as in Fig. 15, with a set of tubes carried from end to end, and set as closely as is practicable without interfering too seriously with the circulation of the water within it.

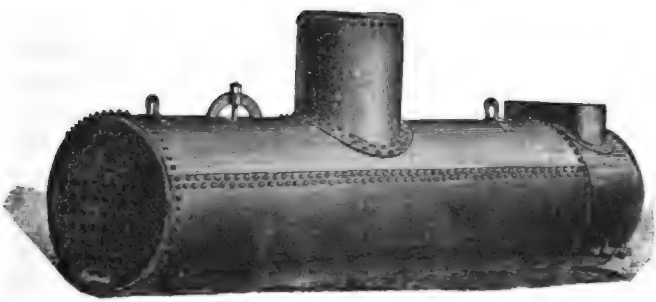

FIG. 18.—CYLINDRICAL TUBULAR BOILER.

The peculiar feature of the illustration is the introduction of the very large single sheet which is seen to make the whole lower two thirds or more of the shell; this construction pre-

venting the fire reaching seams and riveting, as occurs in the usual construction.

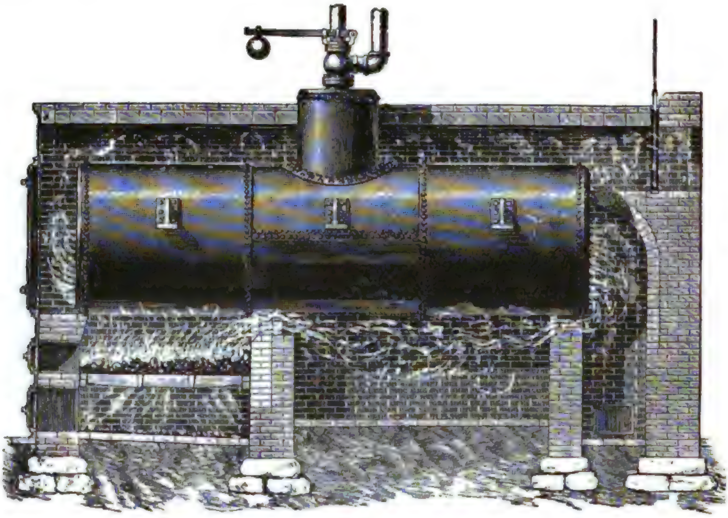

FIG. 19.—CYLINDRICAL TUBULAR BOILER AND SETTING.

The setting of this kind of boiler is shown in Figs. 19 and 20. The weight of the boiler is here taken by "lugs" on each side and by them transferred to the brickwork of the setting. In other cases the boiler is suspended from girders crossing the structure laterally; and the suspension-rods carrying the boiler are sometimes allowed vertical play, under the action of expansion and contraction of the whole system, by the introduction of springs of rubber or steel, thus permitting very uniform distribution of the weight at all times. In many cases the gases, instead of being carried over the boiler to the chimney, as shown in Fig. 19, are taken directly to the chimney from the front of the boiler, as

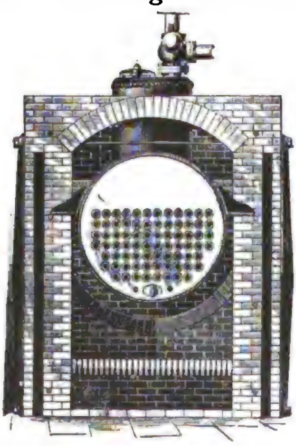

FIG. 20.—SECTION OF TUBULAR BOILER AND SETTING.

in Fig. 16. It is not always thought safe to expose the top and steam spaces of the boiler to the heat of the escaping gases; but the practice is not an uncommon one, even with reputable builders. The air-spaces in Fig. 20, at either side in the walls of the setting, give an additional protection from loss of heat, and a certain amount of elasticity of setting. This is the most common of all forms of steam-boiler.

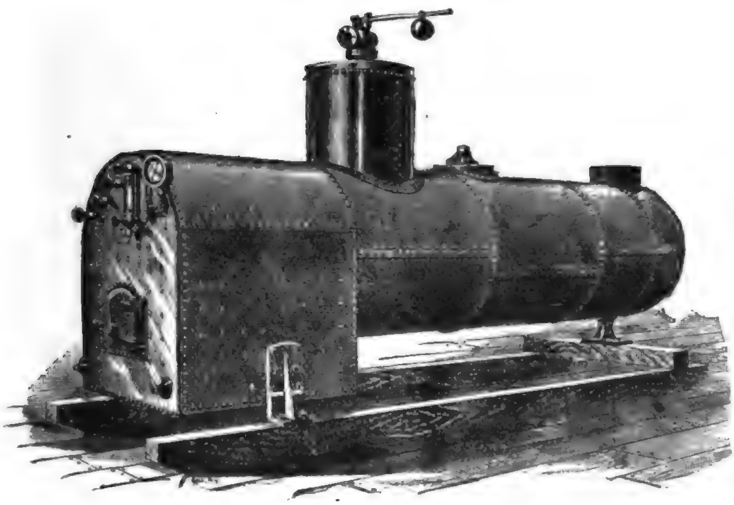

FIG. 21.—FIREBOX TUBULAR BOILER.

(4) *The Firebox Flue Boiler* is so made in order that the whole may become "self-contained," and brickwork dispensed with. Adding the firebox to the tubular (Fig. 21), forms the locomotive type of boiler. In stationary boilers, however, the tubes are, as a rule, larger and less numerous than in the locomotive boiler. These boilers require no setting or connections other than the parts needed to connect them with the chimney-flue.

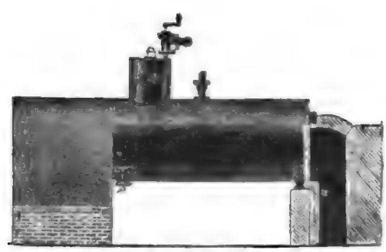

FIG. 22.—FIREBOX BOILER SETTING.

This arrangement is seen in Fig. 22. The advantages of this type are the low cost of installation, the more complete ac-

cessibility of the exterior for inspection and repair, the reduction of floor-space occupied, and the portability of the boiler.

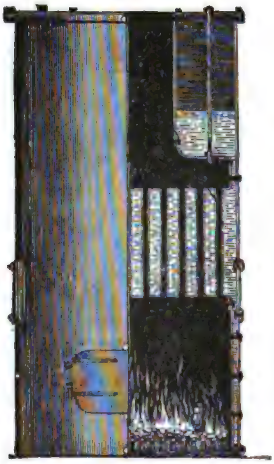

FIG. 23.—THE UPRIGHT BOILER.

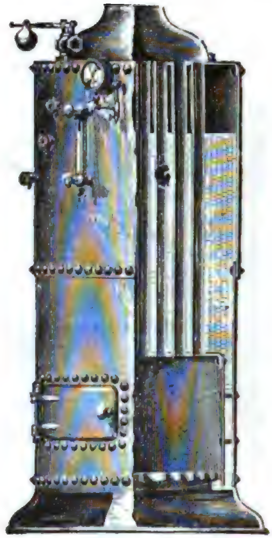

FIG. 24.—UPRIGHT TUBULAR BOILER.

(5) *The Upright Boiler* is usually a firebox tubular boiler, designed to stand vertically, as in Fig. 23, and to occupy mini-

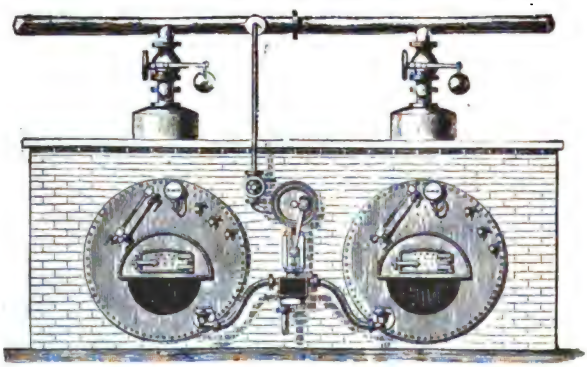

FIG. 25.—BATTERY OF BOILERS.

The above cut represents a pair of Cornish boilers set in brick-work, connected so as to be worked either together or separately.

mum floor-space. Its construction at the upper end is often such as to permit the upper extremities of the tubes to be kept be-

low the water-line. In many cases, however, the tubes are carried directly through to the upper head, as is seen in Fig. 24. This figure also exhibits the method of attaching gauges and safety-valves. This boiler is much used where it is important to save floor-space, and where head-room can be obtained. It is the usual form in steam fire-engines.

FIG. 26.—UPRIGHT BOILER WITH FIELD TUBES.

16. **A "Battery" of Boilers** (Fig. 25) consists of two or more, placed side by side, the total power demanded being greater than it is considered advisable to construct a single boiler to supply. In such cases it is usually important that they should be so set and connected that either or any of them may be operated separately. To secure this result, the connections with the feed and steam-pipes must be so made that it may be perfectly practicable to put the feed on either or any of the boilers in the battery, and to take steam from either or any. Each should have its own separate safety-valve, check-valve, and steam-gauge.

An upright boiler fitted with "Field tubes" is shown in Fig. 26. The internal, circulating, tubes project slightly above the crown-sheet, and are carried down inside the main tube, nearly to the closed lower end. The water enters the centre tube, flows out at its lower end, and rises in the outer tube —on all sides the smaller one—issuing above the crown-sheet into the general body of water, and there discharging the accompanying steam which had been made during the period of circulation.

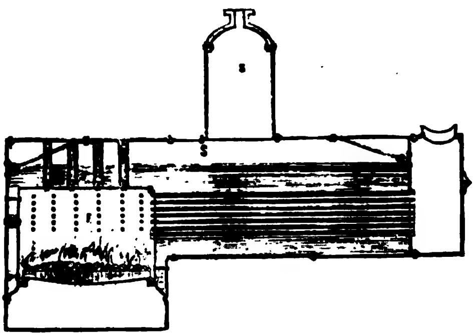

FIG. 27.—LOCOMOTIVE BOILER.

17. **The Locomotive Boiler** is always given a form substantially as represented in Fig. 27, and consists of a firebox of rectangular form, attached to a cylindrical shell closely filled

with fire-tubes, through which the gases pass directly to the smoke-stack. Strength, compactness, great steaming capacity, fair economy, moderate cost, and convenience of combination with the running parts, are secured by the adoption of this form. It is frequently used also for portable and stationary engines. It was invented in France by M. Séguin, and in England by Booth, and used by George Stephenson at about the same time—1828 or 1829.

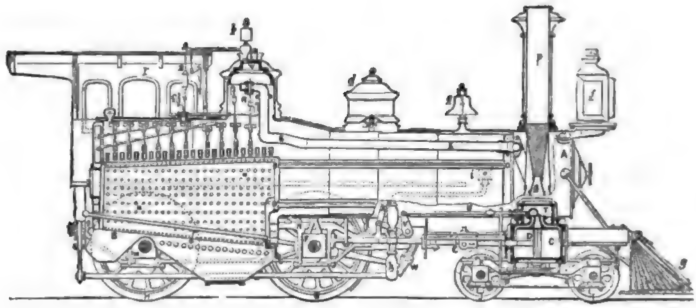

FIG. 28.—THE LOCOMOTIVE. Section.

This form of steam-boiler has been found to lend itself with peculiar handiness to the special requirements of locomotive construction, and its use is universal for this purpose.

18. The "Marine" Boilers are often of very different form from those used on land. They have assumed their present forms after many years of experience and slow adaptation to the special conditions by which they are controlled. When steam-pressures were customarily low, the controlling condition was the form of the vessel, and boilers were given such shapes as would permit of their being compactly stowed on board ship; in the later days of very high pressure which have followed the introduction of the surface-condenser, and of high expansion, the form of the steam-generator is determined mainly by the demand for their safe operation.

Fig. 29 shows one of the types of boiler in most common use on the steamers generally seen on the Eastern American rivers, and on the coast, before the period of high steam and great economy had opened.

It is known as the "Return-flue" boiler, the flame and gases from the furnace passing back to the "back-connection" through one set of flues, usually of 10 to 20 or even 24 inches in diameter, and thence to the "front-connection" over the furnace, and to the "uptake," and chimney or "smokestack," by a set of flues of, as a rule, smaller size and larger number. This is seen to be a "firebox boiler, no brickwork setting being admissible on shipboard.

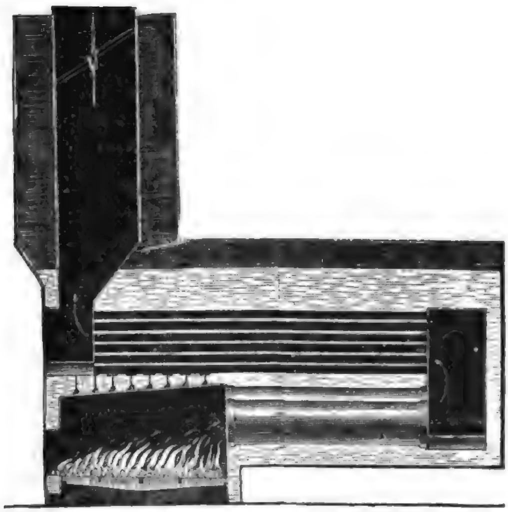

FIG. 29.—FLUES AND RETURN-TUBES.

Surrounding the chimney uptake is a reservoir, called the "steam-chimney," which answers the double purpose of a steam-dome and a drier, or "superheater," in which the steam may part with its suspended water, and often become heated above the temperature of saturation by the heat from the chimney gases. An elaborate system of bracing and staying is required for a boiler of this type. The sketch (Fig. 29) shows one of a pair of boilers arranged to discharge their flue gases into a common chimney.

An effort to secure increased steaming capacity and economy in this boiler resulted in the production of the boiler

with direct flues and return-tubes, the latter being usually from three to five inches in diameter. This represents the later type, and one which is still very often used on paddle-steamers on Long Island Sound and on the rivers connected with that system of water communication.


FIG. 30.—MARINE TUBULAR BOILER.

Fig. 30 illustrates a still more advanced type, the marine tubular boiler, extensively used in naval and other sea-going steamers, carrying from twenty-five to forty pounds steam-pressure. The furnace discharges its gases directly into the back-connection, whence they pass forward into the front connection and stack through a set of tubes, which are commonly $2\frac{1}{2}$ to $3\frac{1}{2}$ inches in diameter. This arrangement gives a very compact, well-proportioned boiler, comparatively easy of calculation and construction, and especially convenient in bracing and staying. Several furnaces can in this boiler be conveniently placed side by side and connected to a common uptake.

19. **The Marine Water-tube Boiler** (Fig. 31) represents a type which has been often proposed for use at sea, but which has never succeeded in finding its way into common use.

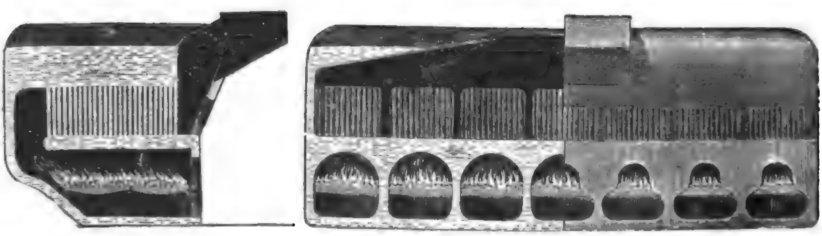
FIG. 31.—MARINE WATER-TUBE BOILER.

Lord Dundonald in Great Britain and James Montgomery in the United States introduced boilers of the water-tube

type before the middle of the century, and the form here illustrated, as originally designed by Mr. Martin of the U. S. Navy, was very extensively employed on the vessels of the navy during the Civil War. In these boilers the gases pass from the back-connection to the front through a "tube-box" placed in the water-space of the boiler, which tube-box contains a large number of vertical tubes within which the water circulates from the lower to the upper side, while the gases pass among and around the tubes.

These boilers were found by Isherwood to give a somewhat larger steaming capacity and greater economy also than the corresponding boiler of the fire-tube type; but the difficulty of repairing leaky tubes and incidental disadvantages, as well as their greater cost, prevented their permanent adoption in either the navy or the merchant service.

20. The Scotch or Drum Boiler (Fig. 32) is the outcome of the attempt to secure a safe form of boiler for high pres-

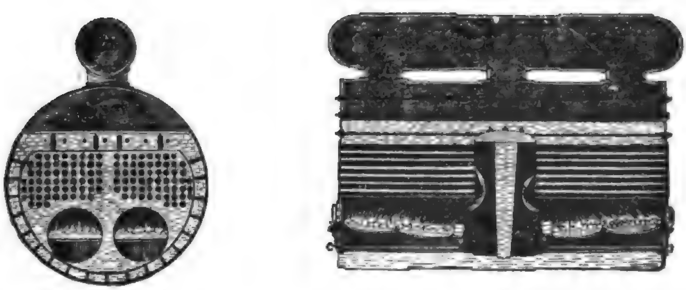

FIG. 32.—SCOTCH OR DRUM BOILER.

sures, and it has, very naturally, assumed the cylindrical form of shell, while retaining the general disposition of furnace and tubes illustrated in the last-described fire-tube boiler. The furnaces are large, set in very thick flues; the grates are set in them at very nearly the horizontal diametrical line, and, in the case illustrated, the boiler is "double-ended." Heavy stay-rods, connecting the two ends, make the heads capable of safely carrying their enormous loads. These boilers often carry 100 and 150 pounds pressure, and sometimes even more,

and are built of between 10 and 20 feet diameter, and of iron or steel from $\frac{5}{8}$ to $1\frac{1}{4}$ inches in thickness.

Fig. 33 exhibits the method of setting and of connection of these boilers, as customarily practised where "single-ended," i.e., with the furnaces at one end only, as here seen. Either or any of these boilers, as so set, may be used or repaired separately if necessary.

For small powers these boilers are often given the form and structure shown in Fig. 31, which represents a boiler designed for a small yacht or a torpedo-boat; it is three or four feet in

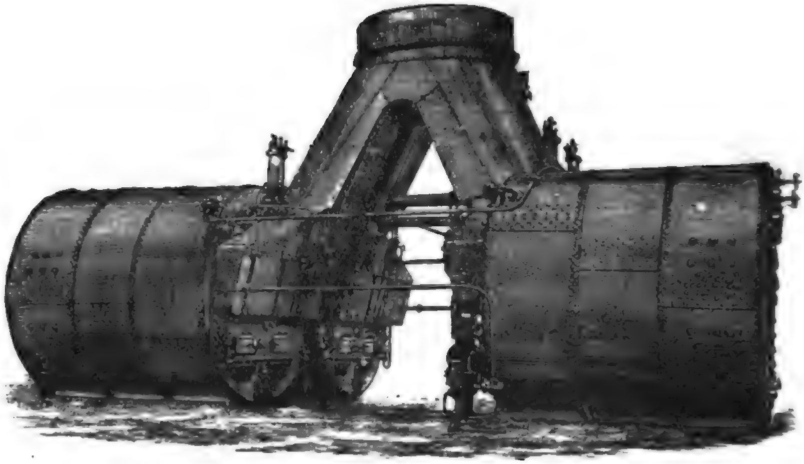

FIG. 33.—SETTING AND CONNECTION OF SCOTCH BOILERS.

diameter and four to six feet long, and is calculated for from five to ten or twelve horse-power.

21. **Sectional Boilers** are all constructed to meet the conditions and requirements so well stated by Col. Stevens in his specification for his British patent of 1805, in which he says that, to derive advantage from his principle, "it is absolutely necessary that the vessel or vessels for generating steam should have strength sufficient to withstand the great pressure from an increase of elasticity in the steam; but this [total] pressure is increased or diminished in proportion to the capacity of the

containing vessel. The principle, then, of this invention consists in forming a boiler by means of a system or combination of a number of small vessels, instead of using, as in the usual mode, one large one; the relative strength of the materials of which these vessels are composed increasing in proportion to the diminution in capacity."

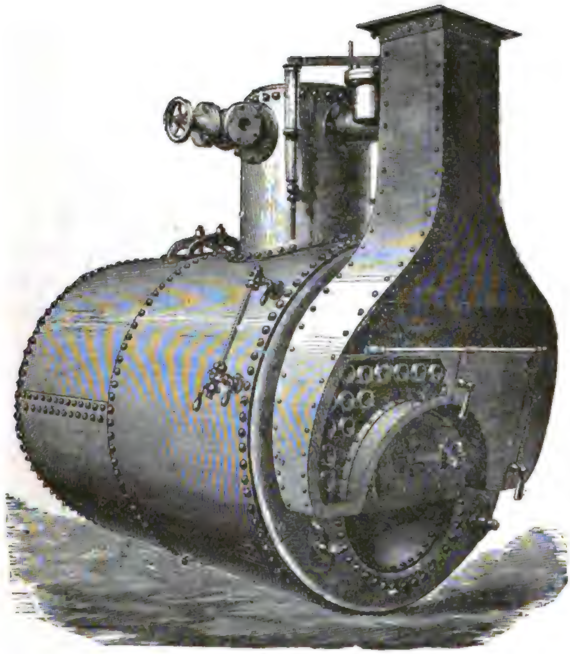

FIG. 34.—MARINE BOILER OF SMALL POWER.

Stevens' boilers were of two kinds: the one that shown in Fig. 10; the other, and that specifically shown in the patent, consisting of systems of small tubes grouped in circular concentric rows, and connected at each end by annular heads and chambers of sufficiently small capacity to be safe, while still large enough to permit good circulation.

The boiler adopted in Gurney's steam-carriage (Fig. 11) is a later type, which has been more than once since reproduced; and nearly all recent, familiar, forms of the sectional boiler are

constructed of systems of tubes united at the ends, and with the feed-apparatus, steam-drum, and mud-drum, by what are known as "headers," through which the general circulation is secured. In some cases the boiler has been made wholly or partly of cast-iron, as the early Babcock & Wilcox (Fig. 35), which consisted of a system of horizontal cast-iron tubes serving both as water connections and as steam-chambers, and a second system of tubes set at a considerable inclination from the horizontal, the two sets united by headers.

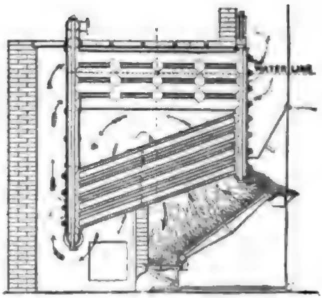

FIG. 35.—CAST-IRON SECTIONAL BOILER.

The Babcock & Wilcox Boiler, in the latest and best form, however (Fig. 36), is wholly of wrought-iron or steel. The same general arrangement of tubes is preserved; but the upper part of the construction consists of one or more steam and water drums of comparatively large diameter. These are away from the fire, and cannot be reached by the gases until they are cooled down to a safe temperature by passing through the lower system of heating surfaces, the inclined tubes. The water-line in the drum is carried at about its middle, and a dry-pipe, seen at the top, carries off the steam made. The joints are all "milled," and so nicely fitted that no practicable pressure can cause leak-

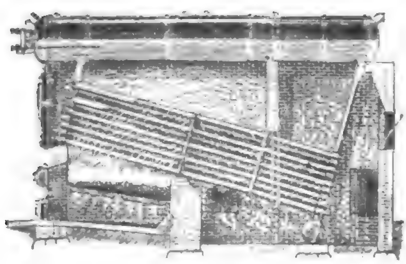

FIG. 36.—BABCOCK & WILCOX BOILER.

age. The course of the furnace gases and the water-circulation can be readily traced in the drawing.

The Root Boiler is shown in Fig. 37, differing from the preceding in the arrangement of tubes and their connection. The form of header is peculiar, and cannot be seen; but the general construction is well shown in the engraving. In various designs, as made at different times and for various purposes, the construction has been somewhat modified, and the location,

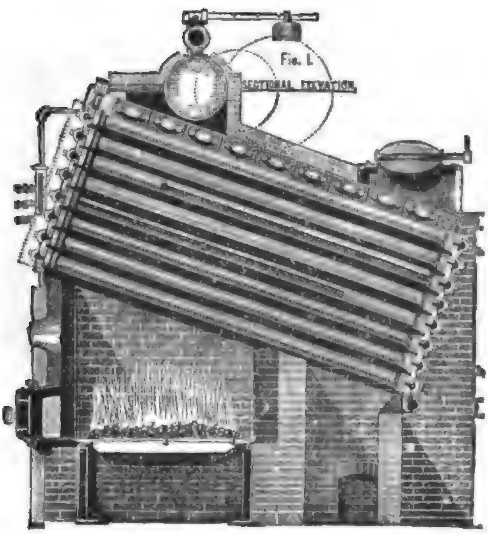

FIG. 37.—THE ROOT BOILER.

size, and number of steam-drums has been varied. The tubes are four or five inches in diameter, and usually eight or ten feet long.

The Harrison Boiler (Fig. 38) consists of an aggregation of spheres, of cast-iron, or steel as now made, connected by "necks" of somewhat smaller diameter. These spheres are 8 inches in diameter, $\frac{5}{8}$ inch thick, capable of sustaining a pressure exceeding 100 atmospheres, and are set in clusters, as shown in the sketch; they are fitted together with faced joints,

and secured by long bolts passing from end to end of each row. These boilers are intended to be so proportioned that a pressure far less than that which would produce rupture will stretch the bolts, thus allowing each joint to act as a safety-

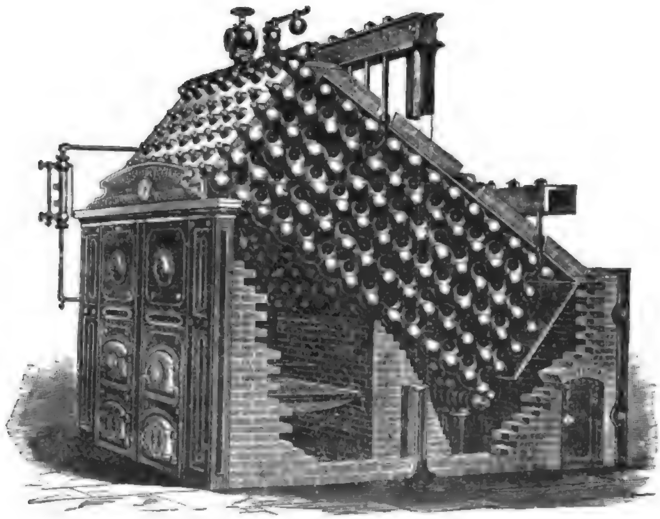

FIG. 38.—THE HARRISON BOILER.

valve. The three types of boiler which have just been described, and their various modifications are the most common and familiar forms of sectional boiler in use.

The Allen Boiler (Fig. 39) has only been constructed experimentally, and has never come into the general market; but experiments made upon it, under the direction of a committee of the American Institute, in 1871, and under the immediate direction of the Author, its chairman, gave excellent results, both in steaming capacity and economy. In this boiler the tubes are suspended by one end, the lower end being closed, as in what is known as the Field system. The inclination of the tubes 30° from the vertical was found by experiment to be best. The horizontal cylinders above, to one of which each line of tubes is connected, serve as circulating tubes and passages by

which the steam made is conducted to the steam-drum. It will be noticed that the whole structure, steam-drum and all, is encased in the brick-work setting and exposed to contact with the heated gases. The circulation within the pendent tubes was excellent, and, with pure water and no sediment or in-

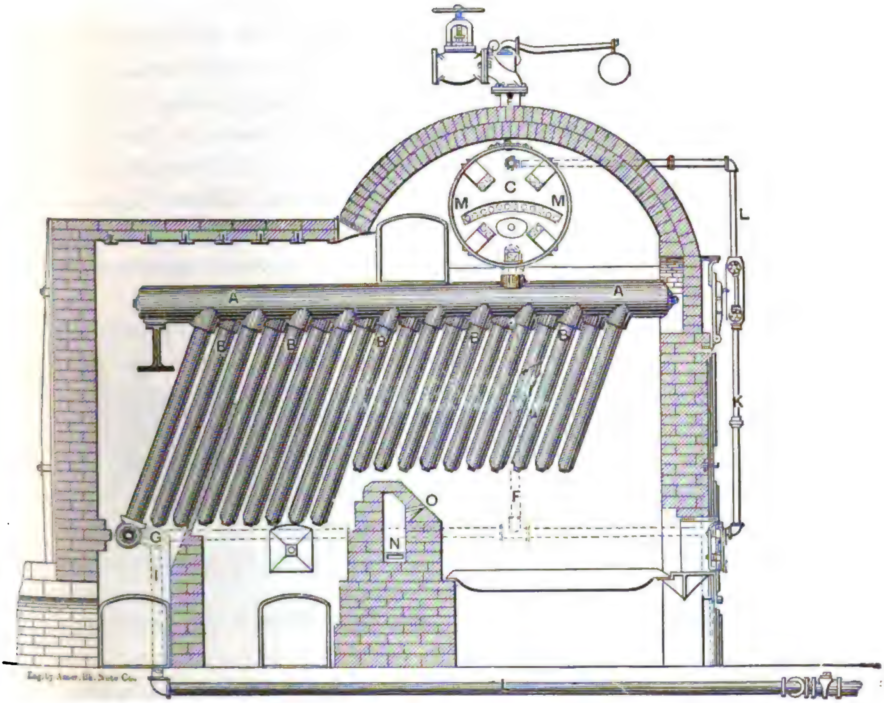

FIG. 39.—THE ALLEN BOILER.

crustation choking them at their lower ends, the boiler was considered capable of doing its work in a very satisfactory manner.

Fairbairn has remarked that "danger in the use of high-pressure steam does not consist in the intensity of the pressure to which the steam is raised, but in the character and construction of the vessel which contains the dangerous element;" and this remark may be taken, like the propositions of Col. John

Stevens, as part of the basis of the philosophy of construction of "sectional" boilers.

22. Marine Sectional Boilers have not as yet come into general use, although many attempts have been made to introduce them. The first boiler built by John Stevens was intended for use in a small steam-vessel; and in 1825 or 1826 Robert L. Thurston and John Babcock, then of Portsmouth, and later of Providence, R. I., built boilers of this class, consisting of coils of pipe within which the water and steam were contained, the fire and furnace gases passing around outside them. Modifications of the Root boiler, known as the Belleville, and others, have been used with success by French builders of marine machinery; and the Babcock & Wilcox Co. have produced a marine boiler like that shown in Fig. 40, a combination of water-tubes below with fire-tubes and steam-space above, which is considered a good form for use at sea.

The necessity of using a brick-work setting has prevented the introduction of the common forms at sea. Many designs are appearing constantly, and it is probably only a question of time, when, with continually rising steam-pressures, the older forms will be displaced by these modern and safer types.

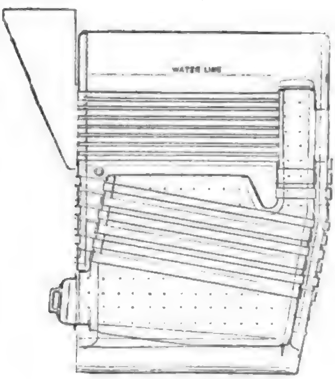

Fig. 40.—Babcock & Wilcox Marine Boiler.

23. The Dates of Introduction of the principal devices noticed in modern boilers have been given by Haswell, who describes the various familiar forms as including the dry-bridge and combustion-chamber of Wright (1756), Dorrance (1845) and Baker (1846); the dead-plate of Watt (1785); the water-bridge of Crampton (1842) and Mills (1851); the air-bridge of Slater (1831); the horizontal fire-tube of Bolton (1780), of Ericsson (1828), Seguin and Booth (1829), and of Hawthorne (1839) and Glasson (1852); the vertical fire-tube of Rumsey (1788); the water-bottom of Allen (1730) and Fraser (1827); the vertical water-leg of Stephens and Hardley

(1748), Napier (1842) and Dundonald (1843); the steam-drum of John Stevens (1803); the superheaters of Hately (1768), of English (1809) and Allaire (who used a tall steam-chimney in 1827).

The hanging bridge of Johnson (1818), the cylindrical return-flue boiler of Napier (1831), the cold-air supply above the fire, as by Thompson (1796), by Robertson (1800), Arnott (1821), and by Williams (1839), are also, he states, features of the modern boiler. The introduction of the water-tube boiler by Montgomery has not led to a change of type.*

These various details will be described more at length in later chapters.

24. Peculiar and Special Forms of Boiler are met with in all departments. Some of these are considerably employed, and in many cases possess special features of advantage. The

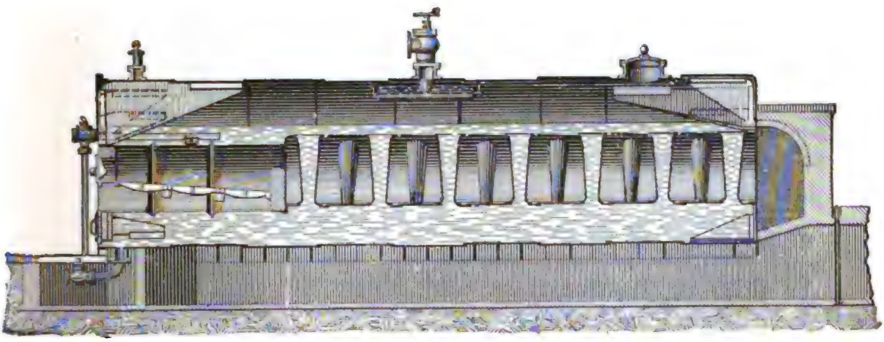

FIG. 41.—THE GALLOWAY BOILER.

Galloway boiler (Figs. 41, 42) is one of the best known and successful modifications of the cylindrical flue-boiler. Its special feature is the conical stay-tube, which is used to increase the heating-surface and to strengthen the flue, without making the heating-surface difficult of access. Large numbers of these boilers have been built and used since about 1860 in Great Britain, and some have been constructed in the United States.

* Trans. British Institution of Naval Architects, 1877.

The exterior is a plain cylindrical shell, within which are two cylindrical furnaces which unite in one flue, having parallel

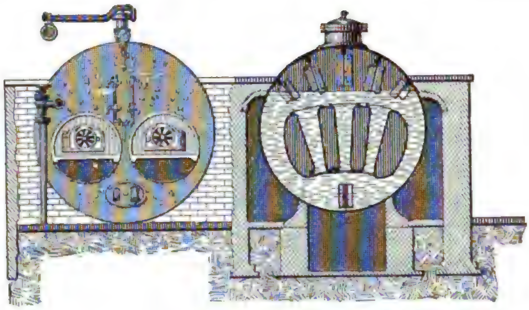

FIG. 42.—GALLOWAY BOILER.

curved top and bottom, struck from a centre below the boiler. In this flue are the conical water-tubes, each 10½ inches diameter at the top and 5½ inches diameter at the bottom, fixed in a radial position and perpendicular to the top and bottom so as to support and brace the flue and to intercept and break up the heated gases in their passage from the furnaces. Along the sides of the flue there are

FIG. 43.—UPRIGHT FLUE-BOILER.

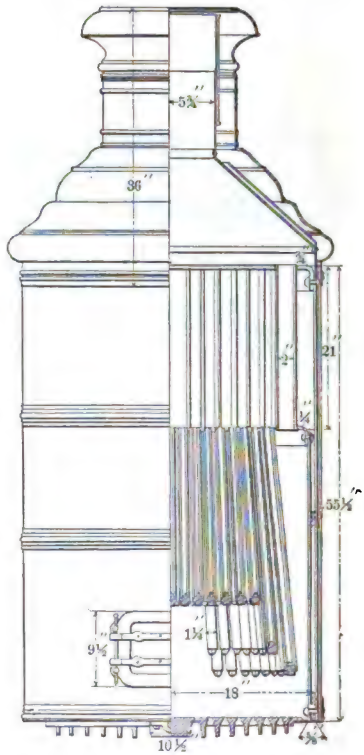

FIG. 44.—FIRE-ENGINE BOILER.

several wrought-iron pockets, or "bafflers," which deflect the currents and cause them to impinge against the tubes the end pocket providing for necessary expansion and contraction. After leaving this flue the gases pass along the sides of the shell to the front end, thence back again under the centre of the boiler to the chimney.

A simple form of upright flue-boiler, for heating purposes and where small power is required, is seen in Fig. 43. It is of simple design, and easy of access for repair.

A steam fire-engine boiler (Fig. 44), as built by the Silsby

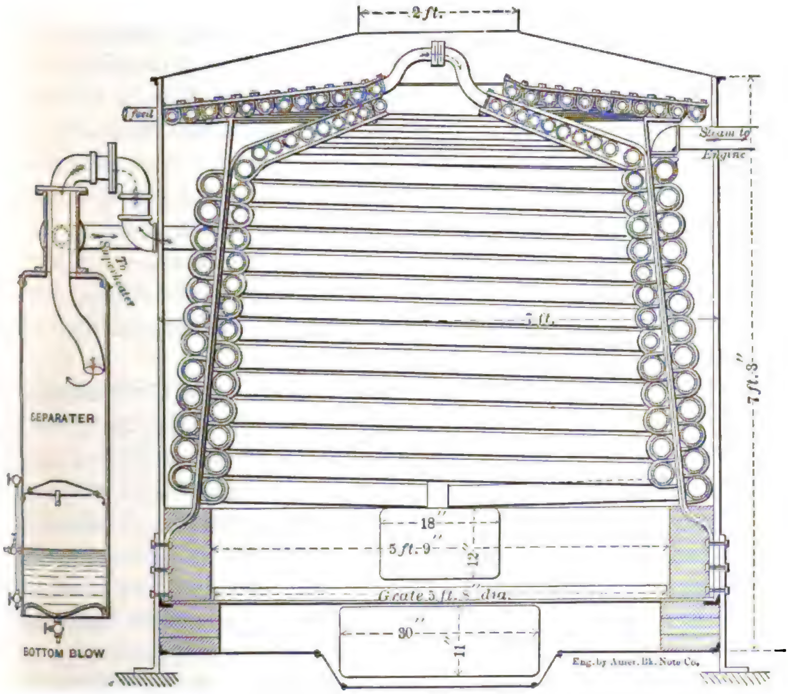

FIG. 45.—HERRESHOFF'S BOILER.

Co. illustrates the use of the Field tubes, pendent from the crown-sheet of the furnace: these are water-tubes, but the gases pass up through the boiler in a set of fire-tubes seen connecting the crown-sheet with the top of the boiler. This makes an exceedingly compact, powerful, and light steam-boiler.

The Herreshoff boiler (Fig. 45), as constructed for fast yachts and torpedo-boats, consists of a cone-shaped double coil of continuous wrought-iron pipe, five feet to five and a half feet in diameter, covered by a disk made up of a coil of smaller pipe. The feed-water passes through the latter, and *downward* through the boiler, inside, and then upward again, through the outside coil, finally passing to the separator, whence the steam passes off to the engine, after circulating through the three top-coils of pipe which forms a superheater, drying and superheating the steam *en route*. The water separated from the steam is driven back into the boiler, with the feed-water, by the feed and circulating pumps. The steam-pipe used in making up the boiler is lap-welded, and from $1\frac{7}{8}$ to $2\frac{3}{8}$ inches in diameter outside, and $\frac{3}{16}$ inch in thickness. This boiler, as built for the yacht Leila, contained 22 cubic feet of steam and water space, of which about one third was steam-space; it had 485 square feet of heating-surface, 44 feet of superheating area, or 18.7 feet of heating-surface, and 1.7 feet of superheating surface, per square foot of grate, these areas being measured on the exterior of the tubes. The boiler developed 75 to 80 horse-power. The separator is obviously an essential feature of the system.

25. Problems in Steam-boiler Design and Construction are among the most interesting, as well as important, which arise in the practice of the engineer. These problems may, and usually do, take many distinct forms. It is almost invariably the fact that the quantity of steam to be obtained is specified either as a certain weight of water to be evaporated and an equal weight of steam to be furnished; or a stated amount of power is to be given through a specified form and size of engine, the probable efficiency of which is known or ascertainable; or a stated volume of building, having a known exposure, is to be heated. In such cases the problem presented is to supply the steam so demanded at a minimum total cost, using a type of boiler to be selected with reference to the special conditions of location and use.

It is often necessary, when dealing with a large "plant," to determine how many boilers should be employed, or to what

extent the steam made should be divided up among them: whether a larger number of small boilers should be built or fewer large boilers. The selection of the best type for a specified location is an exceedingly common duty of the engineer. To secure the supply of a given quantity of steam with absolute safety, or with reasonable minimum risk, is another such problem. The usual case demands the production, with certainty and with safety to life and property, of a stated weight of steam, day by day, for long periods of time, at minimum average total expense for the whole period of life of the boilers.

Problems in construction, arising in connection with the design and application of steam-generators, are mainly related to the best methods of putting together the parts of a boiler of which the design has been made, and involve the continual application of a good knowledge of the nature and uses of the materials used, and especially of the facts and principles governing the strength of materials, of parts, and of the structure as a whole. The selection of the best form of joint is a problem in the design of the boiler; but the determination of the best method of making that joint is a problem in construction. Such are all questions relating to the actual performance of work in the shop, the use of tools in the work of building the boiler, and the comparison of methods.

26. Problems in the Use of Steam-boilers are not less important and difficult of solution, often, than those which arise in the production of the design or in its construction. How to obtain a maximum quantity of steam; how to secure dryness and uniformity of quality; how to prolong the life of the structure; and how to effect its preservation most effectively, at least cost in time, money, or loss of use—are only a few examples of the many problems that continually present themselves for immediate solution while the boiler is in service.

27. The General Method of Solution of Problems in Design is to study the case very carefully in the light of all information that can be gained relating to the special conditions affecting it, and then, by comparison of the results of experi-

ence with various boilers under as nearly as may be similar conditions, determining the best form for the case in hand. The designing engineer next endeavors to effect such improvement as his own talent and experience may enable him to originate, with a view to the most perfect possible adaptation of the design to its purposes. He next settles the general proportions, the forms of details, and finally the absolute dimensions and exact proportions. So much being done, he is prepared to make a preliminary study, which deliberately made alterations may convert into a finally complete design.

CHAPTER II.

MATERIALS—STRENGTH OF MATERIALS AND OF THE STRUCTURE.

28. The Quality of the Materials used in the construction of steam-boilers must obviously be very carefully considered. Not only is the steam-boiler expected to bear great strains and high pressures, but the terrible consequences which are liable to follow its rupture make it important that it should sustain its load and do its work with the most absolute safety attainable. The structure is exposed to greater variety of conditions tending to weaken it and to shorten its life than any other apparatus familiar to the engineer; and the results of its failure are more certain to be disastrous to human life, as well as to property. All parts of the boiler are, while under heavy stress, exposed to continually changing temperatures, with, usually, occasional variations extending over two hundred or more degrees Fahrenheit. Nearly every part is liable to corrosion, often of a kind which is the more dangerous because very difficult to detect or to gauge. The boiler is very liable to be subjected to peculiarly severe stresses due to accidental circumstances and to excessive steam-pressure or to deficiency of water.

The material needed for the purposes of the boiler-maker should for all these reasons be as strong, tough, and ductile as it can possibly be made. Of these qualities it is evident that ductility, capability of bearing violent alteration of form without fracture, is even more vitally essential than strength. A lack of tenacity can be met by using more metal, but nothing can make amends for brittleness. Good boiler-plate must possess great strength, and must combine with it great ductility—must have high elastic and total "resilience," as such a combination is termed.

The various parts of the boiler require their material to exhibit somewhat different special qualities: tubes must be tough enough to bear the "upsetting" action of the "expander" by which they are secured in the tube-sheets, and yet must be hard enough to sustain reasonably well the abrading effect of cinder-laden currents of gas; flue-sheets and especially furnace-sheets must be hard, and capable of resisting both the mechanical wear and the corrosive action of the furnace-gases and their burden of coal, ash, and cinder, and must at the same time sustain safely the continual variation of temperature to which they are subjected by the alternate impact of flame and of cold air as the fires are worked. The "shell" of the boiler is less affected by such stresses; but it nevertheless must meet with a greater variety of loading, in a greater number of directions, than perhaps any other known iron structure; every change of pressure within it, every alteration of temperature, every rise or fall of the water-line, produces a variation of the amount and direction of the stresses to which its metal and joints are exposed. Great tenacity combined with ductility is the essential characteristic of all material used in the construction of steam-boilers.

29. The Principles Relating to the Strength of Materials of construction,* and other qualities useful in resisting the strains to which steam-boilers are subject, are very simple and, in the main, well established.

The Resistance of Metal to rupture may be brought into play by either of several methods of stress, which have been thus divided by the Author:

Longitudinal . . .	Tensile: resisting pulling force. Compression: resisting crushing force.
Transverse	Shearing: resisting cutting across. Bending: resisting cross breaking. Torsional: resisting twisting stress.

When a load is applied to any part of a structure or of a machine it causes a change of form, which may be very slight,

* Abridged and adapted from Part II., Chapter IX., "Materials of Engineering," by the Author.

but which always takes place, however small the load. This change of form is resisted by the internal molecular forces of the piece, i.e., by its cohesion. The change of form thus produced is called *strain*, and the acting force is a *stress*.

The *Ultimate Strength* of a piece is the maximum resistance under load—the greatest stress that can exist before rupture. The *Proof Strength* is the load applied to determine the value of the material tested when it is not intended that observable deformation shall take place. It is usually equal, or nearly so, to the maximum elastic resistance of the piece. It is sometimes said that this load, long continued, will produce fracture; but, as will be seen hereafter, this is not necessarily, even if ever, true.

The *Working Load* is that which the piece is proportioned to bear. It is the load carried in ordinary working, and is usually less than the proof load, and is always some fraction, determined by circumstances, of the ultimate strength.

A *Dead Load* is applied without shock, and once applied remains unchanged, as, e.g., the weight of a bridge; it produces a uniform stress. A *Live Load* is applied suddenly, and may produce a variable stress, as, e.g., by the passage of a railway train over a bridge.

The *Distortion* of the strained piece is related to the load in a manner best indicated by strain-diagrams. Its value as a factor of the measure of shock-resisting power, or of resilience, is exhibited in a later article. It also has importance as indicating the ductile qualities of the metal.

The *Reduction of Area of Section* under a breaking load is similarly indicative of the ductility of the material, and is to be noted in conjunction with the distortion.

E.g., a considerable reduction of section with a smaller proportional extension would indicate a lack of homogeneousness, and that the piece had broken at the soft part of the bar. The greater the extension in proportion to the reduction of area in tension, the more uniform the character of the metal.

Factors of Safety.—The ultimate strength, or maximum capacity for resisting stress, has a ratio to the maximum stress

due to the working load, which, although less in metal than in wooden or stone structures, is nevertheless made of considerable magnitude in many cases. It is much greater under moving than under steady "dead" loads, and varies with the character of the material used. For machinery it is usually 6 or 8; for structures erected by the civil engineer, from 4 to 6. The following may be taken as minimum values of this "factor of safety" for the metals:

Material.	Load.		Shock.	
	Dead.	Live.		
Iron and steel, copper and other soft metals.........	5	8	10 +	Ratio of ultimate strength to working load.
The brittle metals and alloys	4	7	10 to 15	

The Proof Strength usually exceeds the working load from 50 per cent with tough metals, to 200 or 300 per cent where brittle materials are used. It should usually be below the elastic limit of the material.

As this limit, with brittle materials, is often nearly equal to their ultimate strength, a set of factors of safety, based on the elastic limit, would differ much from those above given for ductile metals, but would be about the same for all brittle materials, thus:

Material.	Load.		Shock.	
	Dead.	Live.		
Ferrous and soft metals....	2	4	6	Ratio of elastic Resistance to working load.
Brittle metals and alloys...	3	6	8 to 12	

The figure given for shock is to be taken as approximate, but used only when it is not practicable to calculate the energy of impact and the resilience of the piece meeting it, and thus to make an exact calculation of proportions.

The Measure of Resistance to Strain is determined in form

by the character of the *stress*. By stress is here understood the force exerted, and by strain the change of form produced by it.

Tenacity is resistance to a pulling stress, and is measured by the resistance of a section, one unit in area, as in pounds or tons on the square inch, or in kilogrammes per square centimetre or square millimetre. Then if T represents the tenacity and K is the section resisting rupture, the total load that can be sustained is, as a maximum,

$$P = TK. \qquad (1)$$

Compression is similarly measured, and if C be the maximum resistance to crushing per unit of area, and K the section, the maximum load will be

$$P = CK. \qquad (2)$$

Shearing is resisted by forces expressed in the same way, and the maximum shearing stress borne by any section is

$$P = SK. \qquad (3)$$

Bending Stresses are measured by moments expressed by the product of the bending effort into its lever-arm about the section strained, and if P is the resultant load, l the lever-arm, and M the moment of resistance of the section considered,

$$Pl = M. \qquad (4)$$

Torsional Stresses are also measured by the moment of the stress exerted, and the quantity of attacking and resisting moments is expressed as in the last case.

Elasticity is measured by the longitudinal force, which, acting on a unit of area of the resisting section, if elasticity were to remain unimpaired, would extend the piece to double its original length. Within the limit at which elasticity is unimpaired, the variation of length is proportional to the force acting, and if E is the "*Modulus of Elasticity*," or "Young's Mod-

ulus," l the length, and e the extension, P being the total load, and K the section,

$$E = \frac{Pl}{eK}; \quad \ldots \ldots \quad (5)$$

$$e = \frac{Pl}{EK}. \quad \ldots \ldots \quad (6)$$

The Coefficients entering into these several expressions for resistance of materials are often called *Moduli*, and the forms of the expressions in which they appear are deduced by the Theory of the Resistance of Materials, and the processes are given in detail in works on that subject.

These moduli or coefficients, as will be seen, have values which are rarely the same in any two cases; but vary not only with the kind of material, but with every variation, in the same substance, of structure, size, form, age, chemical composition or physical character, with every change of temperature, and even with the rate of distortion and method of action of the distorting force. Values for each familiar material, for a wide range of conditions, will be given in the following pages.

When a piece of metal is subjected to stress exceeding its power of resistance for the moment, and gradually increasing up to the limit at which rupture takes place, it yields and becomes distorted at a rate which has a definitely variable relation to the magnitude of the distorting force; this relation, although very similar for all metals of any one kind, differs greatly for different metals, and is subject to observable alteration by every measurable difference in chemical composition or in physical structure.

Thus in Fig. 46 let this operation be represented by the several curves a, b, c, d, etc., the elevation of any point on the curve above the axis of abscissas, OX, being made proportional to the resistance to distortion of the piece, and to the equivalent distorting stress, at the instant when its distance from the left side of the diagram, or the axis of ordinates, OY, measures the coincident distortion. As drawn, the strain-diagram, $a\ a'$, is such as would be made by a soft metal like tin or lead; $b\ b'$

represents a harder, and $c\ c'$ a still harder and stronger metal, as zinc and rolled copper. If the smallest divisions measure the per cent of extension horizontally, and 10,000 pounds per square inch (703 kilogrammes per square centimetre) vertically, $d\ d'$ would fairly represent a hard iron, or a puddled or a "mild" steel; while $f\ f'$ and $g\ g'$ would be strain-diagrams of hard and of very hard tool steels, respectively.

The points marked e, e', e'', etc., are the so-called "*elastic limits*," at which the rate of distortions more or less suddenly changes, and the elevation becomes more nearly equal to the permanent change of form, and at these points the resistance to further change increases much more slowly than before.

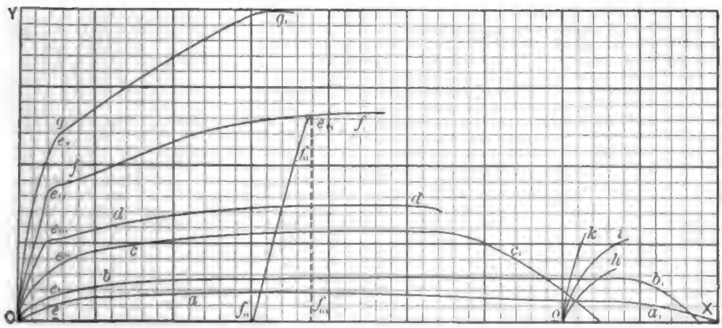

FIG. 46.—STRAIN-DIAGRAMS.

This change of rate in increase in resistance continues until a maximum is reached, and, passing that point, the piece either breaks, as at f' and g', or yields more and more easily until distortion ceases, or until fracture takes place, and it becomes zero at the base-line, as at X.

Such curves have been called by the Author "Strain-diagrams."

If at any moment the stress producing distortion is relaxed, the piece recoils and continues this reversed distortion until, all load being taken off, the recoil ceases and the piece takes its "permanent set." This change is shown in the figure at $f''\ f'$, the gradual reduction of load and coincident partial restoration of shape being represented by a succession of points

forming the line $f'' f''$, each of which points has a position which is determined by the elastic resistance of the piece as now altered by the strain to which it has been subjected. The distance $O f''$ measures the permanent set, and the distance $f'' f'''$ measures the recoil.

The piece now has qualities which are quite different from those which distinguished it originally, and it may be regarded as a new specimen and as quite a different metal. Its strain-diagram now has its origin at f'', and the piece being once more strained, its behavior will be represented by the curve $f' f' e^{VI} f$, a curve which often bears little resemblance to the original diagram O, f, f'. The new diagram shows an elastic limit at e^{V}, and very much higher than the original limit e^{IV}. Had this experiment been performed at any other point along the line $f f'$, the same result would have followed. It thus becomes evident that the strain-diagram is a curve of elastic limits, each point being at once representative of the resistance of the piece in a certain condition of distortion, and of its elastic limit as then strained.

The ductile, non-ferrous metals, and iron and steel and the truly elastic substances, have this in common—that the effect of strain is to produce a change in the mode of resistance to stress, which results in the latter in the production of a new and elevated elastic limit, and in the former in the introduction of such a limit where none was observable before.

It becomes necessary to distinguish these elastic limits in describing the behavior of strained metals, and, as will be seen subsequently, the elastic limits here described are under some conditions altered by strain, and we thus have another form of elastic limit to be defined by a special term.

In this work the original elastic limit of the piece in its ordinary state, as at e, e', e'', etc., will be called either the *Original* or the *Primitive*, *Elastic Limit*, and the elastic limit corresponding to any point in the strain-diagram produced by gradual, unintermitted strain will be called the *Normal Elastic Limit* for the given strain. It is seen that the diagram representing this kind of strain is a *Curve of Normal Elastic Limits*.

The elastic limit is often said to be that point at which a

permanent set takes place. As will be seen on studying actual strain-diagrams to be hereafter given, and which exhibit accurately the behavior of the metal under stress, there is no such point. The elastic limit referred to ordinarily, when the term is used, is that point within which *recoil* on removal of load is approximately equal to the elongation attained, and beyond which *set* becomes nearly equal to total elongation.

It is seen that, within the elastic limit, sets and elongations are similarly proportional to the loads, that the same is true on any elastic line, and that loads and elongations are nearly proportional everywhere beyond the elastic limit, within a moderate range, although the total distortion then bears a far higher ratio to the load, while the sets become nearly equal to the total elongations.

The behavior of metals under moving or "live" load and under shock is not the same as when gradually and steadily strained by a slowly applied or static stress. In the latter case the metal undergoes the changes illustrated by the strain-diagrams, until a point is reached at which equilibrium occurs between the applied load and resisting forces, and the body rests indefinitely, as under a permanent load, without other change occurring than such settlement of parts as will bring the whole structural resistance into play.

When a freely moving body strikes upon the resisting piece, on the other hand, it only comes to rest when all its kinetic energy is taken up by the resisting piece; there is then an equality of *vis viva* expended and work done, which is expressed thus:

$$\frac{WV^2}{2g} = \int_0 p dx = p_m s; \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (7)$$

in which expression W is the weight of the striking body, V its velocity, p the resisting force at any instant, p_m the mean resistance up to the point at which equilibrium occurs, and s is the distance through which resistance is met.

As has been seen, the resistance may usually be taken as varying approximately with the ordinates of a parabola, the

abscissas representing extensions. The mean resistance is, therefore, nearly two thirds the maximum, and

$$\frac{WV^2}{2g} = \int_0^s p\,dx = p_m s = \tfrac{2}{3}et = ae^2, \text{ nearly}, \quad . \quad . \quad (8)$$

where e is the extension, and t the maximum resistance at that extension, and a a constant. Brittle materials, like hard bronzes and brasses, have a straight line for their strain-diagrams, and the coefficient becomes $\frac{1}{2}$ instead of $\frac{2}{3}$, and

$$\frac{WV^2}{2g} = ae^2 = \tfrac{1}{2}et = \tfrac{1}{2}\frac{t^2}{E}. \quad . \quad . \quad . \quad . \quad . \quad (9)$$

Resilience, or Spring, is the work of resistance up to the elastic limit. This will be called *Elastic Resilience.* The modulus of elasticity being known, the Modulus of Elastic Resilience is obtained by dividing half the square of the maximum elastic resistance by the modulus of elasticity, E, as above, and the work done to the "primitive elastic limit" is obtained by multiplying this modulus of resilience by the volume of the bar.*

The total area of the diagram, measuring the total work done up to rupture, will be called a measure of *Total* or *Ultimate Resilience.* Mallett's Coefficient of Total Resilience is the half product of maximum resistance into total extension. It is correct for brittle substances and all cases in which the primitive elastic limit is found at the point of rupture. With tough materials, the coefficient is more nearly two thirds— and may be even greater where the metal is very ductile, as, e.g., pure copper, tin, or lead. Unity of length and of section being taken, this coefficient is here called the Modulus of Resilience.

When the energy of a striking body exceeds the total resilience of the material, the piece will be broken. When the

* Rankine and some other writers take this modulus as $\frac{t^2}{E}$ instead of $\frac{1}{2}\frac{t^2}{E}$.

energy expended is less, the piece will be strained until the work done in resistance equals that energy, when the striking body will be brought to rest.

As the resistance is partly due to the *inertia* of the particles of the piece attacked, the strain-diagram area is always less than the real work of resistance, and at high velocities may be very considerably less, the difference being expended in the local deformation of that part of the piece at which the blow is received. In predicting the effect of a shock it is, therefore, necessary to know not only the energy stored in the moving mass and the method of variation of the resistance, but also the striking velocity. To meet a shock successfully, it is seen that resilience must be secured sufficient to take up the shock without rupture, or, if possible, without serious deformation. It is in most cases necessary to make the *elastic* resilience greater than the maximum energy of any attacking body.

Moving Loads produce an effect intermediate between that due to static stress and that due to the shock of a freely moving body acting by its inertia wholly; these cases are, therefore, met in design by the use of a high factor of safety, as above.

As is seen by a glance at the strain-diagram, ff (Fig. 46), the piece once strained has a higher elastic resilience than at first, and it is therefore safer against permanent distortion by moderate shocks, while the approach of permanent extension to a limit renders it less secure against shocks of such great intensity as to endanger the piece.

When the shock is completely taken up, the piece recoils, as at $e^{vi}f''f''$, until it settles at such a point on that line—assuming the shock to have extended the piece to the point e^{vi}—that the static resistance just equilibrates the static load. This point is usually reached after a series of vibrations on either side of it has occurred. With perfect elasticity, this point is at one half the maximum resistance, or elongation, attained. Thus we have

$$\int_0^s p dx = \frac{WV^2}{2g}; \quad . \quad . \quad . \quad . \quad . \quad . \quad (10)$$

but p varies as Δx within the elastic limit, which limit has now risen to some new point along the line of normal elastic limits, as e^{vi}. Taking the origin at the foot of $f''f''$, since the variations of length along the line Ox are equal to the elongations and to the distances traversed as the load falls, and as stresses are now proportional to elongations,

$$p = ax; \quad Wh = Ws; \quad \text{and} \quad W = P; \quad . \quad . \quad . \quad (11)$$

when the resisting force is p, the elongations x, while h and s are maximum fall and elongation, and P is the maximum resistance to the load at rest. Then

$$\int_0^s pdx = a\int_0^s xdx = \frac{a}{2}s^2 = Ws; \quad \therefore s = \frac{2W}{a}. \quad . \quad (12)$$

For a static load, if s' is the elongation,

$$W = P = as'; \quad \therefore s' = \frac{W}{a}.$$

Hence,

$$\frac{s'}{s} = \tfrac{1}{2}, \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (13)$$

and the extension and the corresponding stress due to the sudden application of a load are double those produced by a static load.

Where the applied load is a pressure and not a weight, i.e., where considerable energy in a moving body is not to be absorbed, as in the action of steam in a steam-engine, the only increase of strain produced by a suddenly applied load is that produced by the inertia of such of those parts of the mass attacked as may have taken up motion and energy.

30. **Tenacity, Elasticity, Ductility, and Resilience** are the four essential qualities of a good material for use in steam-boiler construction. In some cases, the relative values of

these several properties are very different from that relation in others. For example: while boiler-iron or steel must have ductility, even if tenacity is sacrificed to some extent to secure it, machinery irons and steels should have a certain amount of rigidity, and tool-steel a minimum allowable hardness, as their leading characteristics; and in all, the essential property being secured, as good a combination of all the other valuable properties is sought as can possibly be obtained.

The problem of proportioning parts to resist shock is seen to involve a determination of the energy, or "living force," of the load at impact, and an adjustment of proportion of section and shape of piece attacked such that its work of elastic or of ultimate resilience, whichever is taken as the limit, shall exceed that energy in a proportion measured by the factor of safety adopted. For ordinary live loads and moderate impact, requiring no specially detailed consideration, the factors of safety already given, as based upon ultimate strength simply, are considered sufficient; in all cases of doubt, or when heavy shock is anticipated, calculations of energy and resilience are necessary, and these demand a complete knowledge of the character, chemical, physical, and structural, of every piece involved, of its resilience and method of yielding under stress, and of every condition influencing the application of the attacking force—in other words, a complete knowledge of the material used, of the members constructed of it, and of the circumstances likely to bring about its failure.

The form of such parts should usually be determined on the assumption that deformation may some time occur; and such expedients as that of Hodgkinson in enlarging the section on the weaker side, as well as the adoption of a larger factor of safety based on ultimate strength, are advisable.

31. The Chemical and Physical Characteristics of Iron determines the value of the metal for the purpose of the engineer in construction. The following set of strain-diagrams (Fig. 47) may be taken as representative of the behavior of good samples of the various grades of wrought-iron and of steel above described.

The diagrams *a a*, *b b*, *c c*, are those of commercial irons of

good quality, soft, medium, and hard respectively, and all of high ductility. The elastic limits of *a* and *b* differ greatly in position, and the irons themselves are characteristically different. The one is in a condition of initial internal strain which has weakened it against external stresses; but that strain being relieved by flow under strain, the iron is finally found to be stronger than the second piece.

It is evident that the first is less valuable than the second,

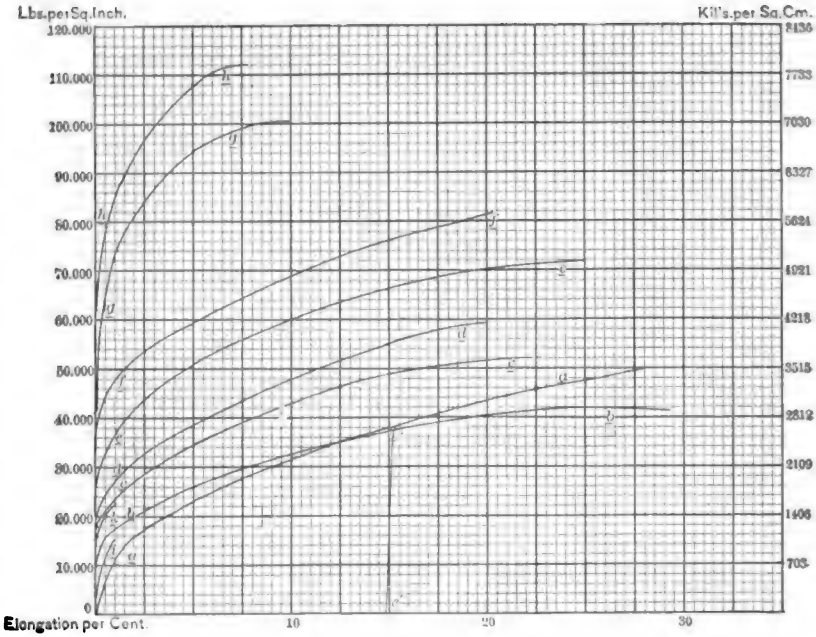

FIG. 47.—STRAIN-DIAGRAMS OF IRON AND STEEL.

however, under any stresses that occur within the usual limits of distortion; the engineer would choose *b* as having a higher elastic limit and much greater elastic resilience.

The "elasticity line," *e′ e′*, shows the amount of spring and of set at the point at which it is taken, and gives a measure of the modulus of elasticity. The harder iron, *d d*, is probably actually a puddled steel, and has been made by balling up the sponge in the puddling furnace too early to permit complete

reduction of carbon. The gradual increase in strength, with increase of carbon, and rise of the elastic limit, are shown, as well as the coincident loss of ductility, in the diagrams, *e*, *f*, *g*, and *h*, which are those of steels containing from 0.35 to 1 per cent carbon; *e* and *f* are the diagrams from excellent samples of the product of the open-hearth and pneumatic processes, and the stronger specimens are representatives of the average crucible steel.

The increase of resilience within the elastic range is seen to be very great as the percentage of carbon is increased.

The chemical composition of iron and steel determines the real character of any sample, although differences of physical character and of molecular structure often seriously modify the value of pieces into the composition of which they enter. With cast metal, where sound castings have been secured, the chemical constitution of the metal being known from analyses, the value of the metal for purposes of construction may be usually well judged; and a comparison of the data given by the chemist with the specific gravity of the metal, will generally be sufficient to determine its character with great exactness. Specifications for cast-iron or cast-steel may usually be safely so drawn as to make the acceptance of the material dependent upon accordance with specified formulas of composition and density.

Thus: A good, gray foundry iron, free from phosphorus and low in silicon, and having a density of 7.25 to 7.28, is, unless containing some peculiar and unusual constituent in excess, a safe iron to use for all purposes demanding strength Wrought-iron and "mild" steels are, on the other hand, so greatly modified by the processes of preparation in the mill, that actual test can only be safely depended upon to determine their value in construction.

Statements of the strength of iron or steel are not of great value in any case, when the metal of which the strength or ductility is given is specified by its trade or generic name simply without a statement of its precise chemical composition and physical character. Wrought-iron varies in composition and in structure to such an extent that, while the softest and purest

varieties often have a tenacity of but about 40,000 pounds per square inch (2812 kilogrammes per square centimetre), some so-called wrought-irons (properly puddled steels) have been met with by the Author in the market having a tenacity of double that figure; some samples extend 25 per cent before breaking, while others, with similar shape and size of test-piece are found nearly as brittle as cast-iron.

Cast-iron varies in tenacity from as low as 10,000 pounds per square inch (703 kilogrammes per square centimetre) to more than 50,000 pounds (3515 kilogrammes per square centimetre); while metals are sold under the name of "steel" having tenacities varying from that of wrought-iron up to over 100 tons per square inch (15,746 kilogrammes per square centimetre).

In the examples of results of tests of iron and steel which will be hereafter given, therefore, the character of the metal tested will usually be exactly defined by its chemical composition.

In comparing the results of test with the chemical constitution of the material, it will be found that, in general, elements which increase tenacity also decrease ductility and resilience.

Thus: carbon increases strength up to a limit beyond which an excess begins to weaken it, as at the limit which separates steel from cast-iron; but every addition of strength takes place at the sacrifice of that ductility which is an essential property of good iron.

Phosphorus adds strength, as do manganese and other less common constituents; but in each case a limit to increasing strength is reached, and in each case the increase of strength noted is accompanied by an equally or more noticeable loss of ductility. It sometimes happens, however, that the elastic resilience increases, with addition of such elements, up to a limit; which limit is, however, reached long before the increase of strength ceases.

The influence of the most common hardening elements upon the valuable qualities of "rail-steel" and similar metals has not been studied sufficiently to determine their precise effect and their modifying action as mutually reacting upon each other.

The hardening elements most usually met with in iron and steel are carbon, silicon, manganese, and phosphorus. Dr. Dudley* takes the effect of manganese, carbon, silicon, and phosphorus to be as the numbers 3, 5, 7½, and 15, and reckons the sum of their effects in "phosphorus units" on this basis, allowing 0.05, 0.03, 0.02, and 0.01 per cent respectively of these elements, taken in the order just given, as each equivalent to one unit. He concludes that the sum should not exceed 31 or 32 in rails and other soft ingot-metals, this figure being obtained, as above, by adding together the phosphorus percentage, one half the silicon, one third the carbon, and one fifth the manganese. Taken singly, the limit for phosphorus is placed at a maximum of 0.10 per cent, silicon at 0.04, manganese at 0.30 or 0.40, and for such metals, carbon at 0.25 to 0.30 per cent. Higher proportions make the material too brittle for rails and similar uses. For boiler-plate these elements should be reduced nearly one half.

Steels containing more carbon are still more carefully chosen with a view to the avoidance of the loss of ductility due to the action of other elements in presence of carbon.

Manganese steels, i.e., steels containing a high percentage of manganese, having but little carbon or other of the hardening elements, are found to have peculiar value for many purposes of construction; but their use must be carefully avoided in steam-boilers, or elsewhere, when exposed to great and rapid changes of temperature.

The chemical composition of cast-iron will usually, and especially if checked by a determination of density, serve well as a guide to the selection of iron of any specified character for use in construction; yet it is always advisable to supplement the analysis by the determination of its physical characteristics as revealed by inspection and by test. The openness or closeness of grain, the shade of color, the depth of chill, and other properties capable of detection by the senses, are valuable guides to the experienced engineer.

The same is true of all forms of ingot metal, whether worked

* Trans. Am. Inst. Mining Engineers, vol. vii.

or unworked. Steels are selected by visual inspection with great accuracy and certainty; but the engineer usually desires to compare the chemist's analysis with the results of mechanical tests, as well as to obtain the judgment of the steel-maker who inspects the topped ingots.

The products of the pneumatic and of the open-hearth processes are now customarily tested both by the chemist's and by physical tests.

The influence of mechanical treatment during the process of manufacturing wrought-iron and puddled steel—the "weld" metals—is very great in the modification of their valuable properties. This is the case to such an extent that the quality of these materials can but rarely be safely judged from chemical analysis. The presence or absence of cinder, the amount of reduction in the rolls or under the hammer, and the temperature and other conditions of working are circumstances that modify quality to such an extent as usually, with the better kinds of metal, to entirely obscure variations due to accidental differences in chemical constitution; with other irons and steels both sets of conditions concur to determine quality. It is never safe, therefore, to base specifications for these materials upon chemical composition alone; actual test is usually demanded as a basis for their acceptance or rejection.

Cast-iron has some advantages as a material for steam-boilers, such as its durability in presence of corroding elements, its freedom from liability to rapid solution by acids, its compact structure and the impossibility of becoming laminated; and it is found to have practically equal conducting power. Its cost is also low; but it is exposed to danger of cracking, either from shrinkage strains or local variations of temperature; it gives no warning when such danger arises, but is always treacherous and unreliable. Its composition is a matter of uncertainty, and is never absolutely known. The cast-iron boilers are usually so constructed that it is easy to substitute a new piece for a broken part, and the boiler is then as good as when new, instead of being weakened by the operation, as is apt to be the case with wrought-iron boilers. On the other hand, they are considered to be commonly somewhat defective in circulation, as a rule.

and deficient in steam-space. Cast-steel is now often substituted for cast-iron in such boilers, and is at once stronger and more trustworthy; it is subject to the same objection as cast-iron in the difficulty met with in securing sound castings. Could good castings be relied upon and shrinkage cracks and strain cracks be prevented, the material would undoubtedly be much more generally employed, especially in small boilers.

32. **Steel for Boilers** is always of the class known as "low," "soft," or "mild" steel, and is, properly speaking, "ingot iron;" all of its characteristics being those of a homogeneous, tenacious, and ductile iron, and quite distinct from those of the true steels. As compared with iron, its greater tenacity, permitting the use of thinner sheets for a given pressure, or giving a greater margin of safety; its greater homogeneousness, insuring more certainty and security in attaining the conditions prescribed in designing; and its greater ductility, which adds enormously to the safety of the structure against dangerous strains and alterations of form: all make it, when of good quality, much the more desirable material. It is rapidly superseding iron in boiler-construction. The difficulties which have retarded its introduction have been mainly those of getting perfect uniformity of composition, not only in successive lots, but also in different parts of the same lot, and even in the same sheet. Many manufacturers have now become able to secure all the uniformity desirable, and to guarantee the quality of their product; from them good boiler-plate can always be obtained.

Steel boiler-plate is usually made by the Siemens-Martin or "open-hearth" process; although considerable quantities are produced from the Bessemer converter, and some by the more costly crucible process. The former possesses peculiar advantages in the making of "mild" steels and boiler-plate in consequence of the facility which it offers for testing the quality of the metal from time to time, while still molten on the furnace-hearth, and then, if it proves not to be of the desired character, modifying it, by addition of such material as may serve to improve it, until the required quality is obtained. While the Bessemer process in skilled hands has produced most excellent

steel, very uniform in grade, neither it nor the crucible process offers such facilities for test and adjustment of quality as characterize the Siemens-Martin system.

The composition of good steel boiler-plate should always be such as will give great ductility and perfect freedom from liability to harden and "take a temper" in consequence of variations of temperature occurring while in use. The carbon should be less in amount than one fourth of one per cent, and it is often less than one tenth. Manganese, which usually constitutes an important element, should be as low as is possible consistent with soundness and homogeneousness. Any boiler-plate that, on being heated to a red-heat and suddenly cooled, is found to harden perceptibly, should be rejected. It should weld readily, and should be capable of sustaining all the tests customarily demanded of boiler-iron even more satisfactorily than the latter. Its ductility should be greater than that of iron.

As ordinarily made, steel is rarely as easily manipulated, and, when subjected to the ordinary operations of boiler-making, seldom exhibits as little loss of quality as the best irons; it must often be very carefully treated, and even in many cases must be annealed after each operation to restore lost ductility. Shearing and punching steels too high in carbon, or containing too much manganese or phosphorus, is very certain to produce injury.

33. The Effect of Variation of Form of a piece of metal, a member, or a structure, is often extremely important. This generally so considerably modifies the apparent tenacity of iron and steel that it is necessary to note the size and shape of the specimen tested before an intelligent understanding of the value of the material can be arrived at by examination of data secured by test. When a piece of metal is subjected to stress and slowly pulled asunder, it will yield at the weakest section first; and if that section is of considerably less area than adjacent parts (Fig. 48), or if the metal is not ductile, it will often break sharply, and without stretching appreciably, as seen in Fig. 50; the fractured surface will have a granular appearance, and the behavior of the piece, as a whole, may be like that of a

brittle casting, even although actually made of tough and ductile metal, when the piece is deeply scored.

When a bar of very ductile metal, of perfectly uniform cross-section (Fig. 49) is broken, on the other hand, it will, at first, if of uniform quality, gradually stretch with a nearly uniform reduction of section from end to end. Toward the ends, where held by the machine, this reduction of area is less perceivable, and on the extreme ends, where no strain can occur, except from the compressing action of the grips, the original area of section

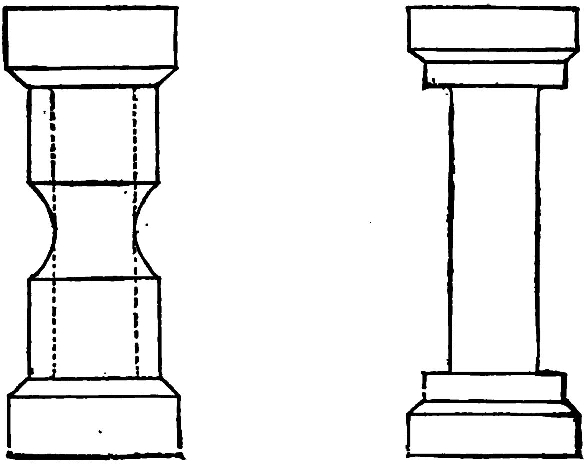

FIG. 48.—Incorrect. FIG. 49.—Correct.

FORMS OF TEST-PIECES FOR TENSION.

is retained, diminution taking place from that point to the most strained part by a gradual taper or by a sudden reduction of section, according to the method adopted of holding the rod. When the stress has attained so great an intensity that the weakest section is strained beyond its elastic limit, "flow" begins there, and, while the extension of other parts continues slowly, the portions immediately adjacent to the overstrained section stretch more and more rapidly as this local reduction of section continues, and finally fracture takes place. This locally reduced portion of the rod has a length which is dependent upon the character of the metal and the size of the piece.

Hard and brittle materials exhibit very little reduction, and the reduced portion is short, as in Fig. 50; ductile and tough metals exhibit a marked reduction over a length of several diameters, and great reduction at the fractured section, as seen in Fig. 51. Of the samples shown in the figures, the first is of a good, but a badly worked, iron, and the second from the same metal after it had been more thoroughly worked.

FIG. 50.

When the breaking section is determined by deeply grooving the test-piece, the results of test are higher by 5 or 10 per cent than when the cylinders are not so cut, if the metal is hard and brittle, and by 20 to 25 per cent with tough and ductile irons or steels. In ordinary work this difference will average at least 20 per cent with the ductile metals. A good bridge or cable iron in pieces of 1 inch (2.54 centimetres) diameter cut from 2-inch (5.08 centimetres) bar, exhibited a tenacity of 50,000 pounds per square inch in long test-pieces, and 60,000 in short grooved specimens (3515 to 4218 kilogrammes per square centimetre). Cast-irons will give practically equal results by both tests, as will hard steels and very coarse-grained hard wrought irons.

FIG. 51.

Since these differences are so great that it is necessary to ascertain the form of samples tested before the results of test can be properly interpreted, it becomes advisable to use a test-piece of standard shape and size for all tests the results of which are to be compared. The figures given hereafter, when not otherwise stated, may be assumed to apply to pieces of one half square inch area (3.23 square centimetres) of section, and at least 5 diameters in length. This length is

usually quite sufficient, and is taken by the Author as a minimum. For other lengths, the extension is measured by a constant function of the total length plus a function of the diameter, which varies with the quality of the metal and the shape of the test-piece. It may be expressed by the formula

$$e = al + f(d). \qquad (1)$$

The elongation often increases from 20 up to 40 per cent as the test-piece is shortened from 5 inches (12.7 centimetres) to ½ inch (1.27 centimetres) in length, while the contraction of section is, on the other hand, decreased from 50 down to 25 per cent, nearly. Fairbairn,* testing good round bar-iron, found that the extension for lengths varying from 10 inches (25.4 centimetres) to 10 feet (3.28 metres) could be expressed, for such iron, by the formula

$$e = 18 + \frac{25}{l}, \qquad (2)$$

where l is the length of bar in inches. In metric measures this becomes

$$e = 18 + \frac{63.5}{l};$$

l = length in centimetres; e = elongation per unit of length.

This influence of form is as important in testing soft steels as in working on iron. Col. Wilmot, testing Bessemer "steel" at the Woolwich Arsenal, G. B., obtained the following figures:

Form.	Test-piece.	Tenacity. Lbs. per sq. in.	Tenacity. Kilogs. per sq. cm.
Grooved, Fig. 48,	Highest	162,974	11,457
	Lowest	136,490	9,595
	Average	153,677	10,803
Long cylinder	Highest	123,165	8,658
	Lowest	103,255	7,259
	Average	114,460	8,047

* Useful Information, second series, p. 301.

The difference amounts to between 30 and 35 per cent, the groove giving an abnormally high figure.

It is evident from the above that the elongation must be proportionably much greater in short specimens than in long pieces. This is well shown below in tests made by Capt. Beardslee for the United States Board.*

TESTS OF TEST-PIECES OF VARYING PROPORTIONS—TENSION.

Number.	Length.		Per cent of Elongation.	Diameter.		Per cent of Contraction of Area.	Stress when Piece began to stretch observably.		Breaking-stress.		Remarks.
	Original.	Final.		Original.	Reduced.		Observed Stress.	Stress per square inch.	Observed Stress.	Stress per square inch.	
	In.	*In.*		*In.*	*In.*		*Lbs.*	*Lbs.*	*Lbs.*	*Lbs.*	
1	5.000	6.522	30.0	.798	.568	49.3	13,400	26,800	26,000	51,989	Elastic limit, 26,795 lbs. per sq. in.
2	3.938	5.204	32.0	.798	.564	50.0	14,000	28,000	26,200	52,389	Elastic limit, 28,194 lbs. per sq. in.
3	4.500	5.853	30.0	.797	.584	46.3	14,000	28,290	26,190	52,495	Elastic limit, 28,062 lbs. per sq. in.
4	3.500	4.605	31.6	.791	.570	48.0	13,000	26.450	26,070	53,052	Elastic limit, 27,268 lbs. per sq. in.
5	3.000	3.977	33.0	.792	.571	48.0	14,000	28,420	26,100	52,984	
6	2.472	3.266	32.1	.799	.589	45.6	14,000	27,920	26,500	52,852	
7	1.989	2.644	32.9	.798	.591	45.0	14,000	28,000	26,500	53,169	
8	1.500	2.026	35.0	.797	.590	45.2	15,500	31,320	26,275	52,666	
9	1.000	1.354	35.4	.798	.600	43.5	16,675	33,350	26,590	53,169	
10	0.500	0.708	41.6	.798	.635	36.6	18,760	37,520	28,665	57.318	

With such brittle materials as the cast-irons, the difference becomes unimportant. Beardslee found a difference of but 1 per cent in certain cases. The more brittle the material the less this variation of the observed tenacity.

As will be seen later, even more important variations follow changes of proportion of pieces in compression. No test-piece should be of very small diameter, as inaccuracy is more probable with a small than with a large piece, and the errors are more likely to be increased in reduction to the stress per square inch. The length should not be less than four times the diameter in any case, and with soft ductile metal five or six diameters would be preferable, for tension.

* Report, p. 104.

Where much work is to be done, it is quite important that a set of standard shapes of test-pieces should be selected, and that all the tests should be made upon samples worked to standard size and form. Thus, tension-pieces are often made of the shapes seen in the figure, when testing square, cylindrical, or flat samples, or samples cut from the solid. The last is a shape called for under the U. S. inspection laws when testing boiler-plate; but it should never be used if choice is permitted, as it gives no chance of stretching, and is therefore nearly useless as a gauge of the quality of the metal; it will undoubtedly be abandoned in course of time, as it invariably gives too high a figure, and does not distinguish the hard and brittle from the better and tougher materials which are desired in construction.

The dimensions adopted by the Author are one-half square inch (3.23 square centimetres) section for all metals except the

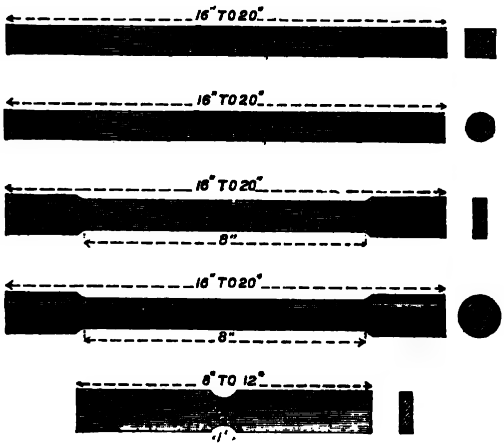

FIG. 52.—SHAPES FOR TEST-PIECES.

tool steels (0.798 inch; 2 centimetres diameter when round), and one-eighth or one-quarter square inch (0.81 to 1.61 square centimetres area; 0.398 or 0.565 inch, 1 or 1.4 centimetres diameter) for the latter, at the smallest cross-section. Kent, who sketches the above, takes these shapes, making them, if of tool steel, $\frac{11}{16}$ inch diameter (1.75 centimetres), or $\frac{3}{8}$ square inch (2.44 square centimetres) area; in other metals either $\frac{3}{4}$ inch (1.9 centimetres)

diameter or 0.44 square inch (2.84 square centimetres), or as above. The edges should be true and smooth, and the fillets ½ inch radius.

For compression tests of metal, 1 inch (2.54 centimetres) long and ½ inch (1.27 centimetres) diameter, ends perfectly square, is recommended; for stone and brick, a 2-inch (5.08 centimetres) cube. Transverse test-pieces should not be less than 1 foot nor more than 4 feet in length, when to be handled in ordinary machines.

The standard specimen will be taken as above, and good wrought-iron of such shape and size should exhibit a tenacity of at least 50,000 pounds (3515 kilograms per square centimetre) if from bars not exceeding 2 inches (5.08 centimetres) diameter, and should stretch 25 per cent with 40 per cent reduction of area. Such test-pieces have the advantage of giving uniform comparable and minimum figures for tenacity, and of permitting accurate determinations of elongation.

Test-pieces are only satisfactory in form when turned in the lathe, as the coincidence of the central line of figure with the line of pull is thus most perfectly insured. When, as with sheet-metal, this cannot be done readily, care must be taken to secure proportions of length and cross-section as nearly like those of the standard test-piece as possible, and to secure symmetry and exactness of form and dimension; such pieces are liable to yield by tearing when not well made and properly adjusted in the machine.

34. **The Method of Treatment** of metal, either previous to its use in any structure or while under load, often seriously modifies its strength, its ductility, and its endurance.

Bar-irons exhibit a wide difference of strength, due to difference of section alone. This variation may be expressed approximately with good irons, such as the Author has studied in this relation, by the formulas

$$\left.\begin{aligned} T &= 56{,}000 - 20{,}000 \log d; \\ T_m &= 4{,}500 - 1{,}406 \log d_m. \end{aligned}\right\} \quad . \quad . \quad . \quad . \quad (1)$$

Where T and T_m measure the tenacity in British and metric

measures respectively, and d and d_m the diameter of the piece, or its least dimension.

Where it is desired to use an expression which is not logarithmic, it will usually be safe to adopt in specifications the following:

$$T = \frac{60,000}{\sqrt[4]{d}}; \quad T_m = \frac{80,000}{\sqrt[4]{d}}. \quad . \quad . \quad . \quad . \quad . \quad (2)$$

The Edgemoor Iron Company adopt, for wrought-iron in tension, the formula

$$T = 52,000 - \frac{7,000A}{B},$$

in which A is the area, and B the periphery of the section.*

The figures in the following table have been taken by the Author as fair values of the tenacity of good average merchant-iron.

TENACITY OF GOOD IRON.

Diameter.		Tenacity, T.	
Centimetres.	Inches.	Lbs. per square inch.	Kilogrammes per square inch.
.64	¼	60,000	4.218
1.27	½	58,000	4,077
1.90	¾	56,000	3.947
2.54	1	55,500	3,902
3.18	1¼	54,500	3,838
3.81	1½	53,500	3.761
4.45	1¾	52.000	3,656
5.08	2	50,000	3,515
5.72	2¼	49,000	3.445
6.35	2½	48,900	3.374
7.62	3	47.500	3.320
8.90	3½	47,000	3,304
10.16	4	46,000	3,234
12.70	5	44,000	3,093

Kirkaldy† found that pieces of 1¼-inch (3.2 centimetres)

* Ohio Railway Report, 1881, p. 379.
† Experiments on Wrought Iron and Steel.

bar rolled down to 1 inch (2.54 centimetres), ¾ inch (1.9 centimetres), and ½ inch (1.27 centimetres) diameter increased in tenacity 20 per cent while decreasing in ductility 5 per cent.

Forging has the same effect as rolling.

The elastic limit is also usually lower in large than in small masses.

Turning iron down has no important effect on the tenacity. The considerable variations always observable in the general rate of increase of tenacity, which, other things being equal, accompanies reduction of size of wire, are due to the hardening of the wire in the draw-plate, and occasional restoration to its softest condition by annealing.

Beardslee has found the change of tenacity in forged and rolled bars to be due to differences in amount of work done in the mill upon the iron. The extent of reduction of the pile sent to the rolls from the heating-furnace is variable, its cross-sectional area being originally from 20 to 60 times that of the bar, the higher figure being that for the smallest bars. On making this reduction uniform, it is found that the tenacity of bars varies much less in different sizes, and that the change becomes nearly uniform from end to end of the series of sizes, and becomes also very small in amount. By properly shaping the piles at the heating-furnace, and by putting as much work on large as on small bars, it was found that a 2-inch (5.08 centimetres) bar could be given a strength superior by over 10 per cent, and a 4-inch (10.17 centimetres) could be made stronger by above 20 per cent than iron of those sizes as usually made for the market. The surface of a bar is usually somewhat stronger than the interior.

The Limit of Elasticity will be found at from two fifths the ultimate strength in soft, pure irons to three fifths in harder irons, and from three fifths in the steels to nearly the ultimate strength with harder steels and cast-irons. Barlow found good wrought-iron to elongate one ten-thousandth its length per ton per square inch up to the limit at about 10 tons. The relation between the *series* of elastic limits and the maximum resistance of the iron or the steel is well shown in strain-diagrams, which exhibit graphically the varying relation

of the stress applied to the strain produced by it throughout the process of breaking.

Repeatedly Piling and Reworking improves the quality of wrought-iron up to a limit at which injury is done by overworking and burning it.

The iron thus treated exhibits increasing strength until it has been reheated five or six times, and then gradually loses tenacity at a rate which seems to be an accelerating one. Forging iron is similar in effect, and improves the metal up to a limit seldom reached in small masses.

The forging of large masses usually includes too often repeated piling and welding of smaller pieces, and it is thence found difficult to secure soundness and strength. This is particularly the case where the forging is done with hammers of insufficient weight. The iron suffers, not only from reheating, but from the gradual loosening and weakening of the cohesion of the metal within the mass at depths at which the beneficial effect of the hammer is not felt.

The Effect of Prolonged Heating is sometimes seen in a granular, or even crystalline, structure of the iron, which indicates serious loss of tenacity. Large masses must always be made with great care, and used with caution and with a high factor of safety. Ingot iron is always to be preferred to welded masses of forged material for shafts of steamers and similar uses.

The Tenacity of Ingot Irons and Steels is less subject to variation by accidental modifications of structure and composition than is that of wrought-iron. The steels are usually homogeneous and well worked, and are comparatively free from objectionable elements, their variation in quality being determined principally by the amount of carbon present, which element occurs in a proportion fixed by the maker, and varying within a very narrow range. The softest grades of ingot iron and steel approach the character of wrought-irons; but their comparative freedom from slag, and their purity, usually make them superior to all ordinary irons in combined strength and ductility. The products of the Bessemer and of the open-hearth processes vary in tenacity from 60,000 pounds per square

inch (4218 kilogrammes per square centimetre) to more than double that figure; while the crucible steels often, and occasionally the preceding, are sometimes four times as strong, a tenacity of 200,000 pounds per square inch (14,060 kilogrammes per square centimetre) being sometimes exceeded.

35. **The Time and the Margin of Stress,** or loading, both affect greatly the life of the piece and the degree of safety with which it may be used.

It has been shown by the Author, and by Commander Beardslee, U. S. N., by direct experiment in the Mechanical Laboratory of the Stevens Institute of Technology, and at the Washington Navy Yard, that the normal elastic limit, as exhibited on strain-diagrams of tests conducted without intermission of stress, is exalted or depressed when intermission of distortion occurs, according as the metal belongs to the iron or to the tin class. This elevation of the normal elastic limit by intermitting strain is, as has been shown, variable in amount with different materials of the iron class, and the rate at which this exaltation progresses is also variable. With the same material and under the same conditions of manufacture and of subsequent treatment the rate of exaltation is quite definite, and may be expressed by a very simple formula. The Author has experimented with bridge material, and Commander Beardslee has examined metal specially adapted for use in chain cables, for which latter purpose an iron is required, as in bridge-building, to be tough as well as strong and uniform in structure and composition. The experiments of the latter investigator have extended to a wider range than have those of the Author, and the effect of the intermission of strains considerably exceeding the primitive elastic limit has been determined by him for periods of from one minute to one year. From a study of the results of such researches and from a comparison with the latter investigation, which was found to be confirmatory of the deduction, the Author has found that, with such iron as is here described, the process of exaltation of the normal elastic limit due to any given degree of strain usually nearly reaches a maximum in the course of a few days of rest after strain, its progress being rapid at first and the rate of in-

crease quickly diminishing with time. For good boiler irons, the amount of the excess of the exalted limit, as shown by subsequent test, above the stress at which the load had been previously removed may be expressed approximately by the formula

$$E' = 5 \log T + 1.50 \text{ per cent};$$

in which the time, T, is given in hours of rest after removal of the tensile stress which produced the noted stretch.

The Author has investigated the action of prolonged stress, using wire of Swedish iron: but one set of samples was annealed; the other, of two sets, was left hard, as drawn from the wire-blocks. The size selected was No. 36, 0.004 inch (0.01 millimetre) diameter, and was loaded with 95, 90, 85, 80, 75, 70, 65, and 60 per cent of the breaking load as obtained by the usual method of test. The result was:

ENDURANCE OF IRON WIRE UNDER STATIC LOAD.

Per Cent Maximum Static Load	Time under Load before Fracture.	
	Hard wire (unannealed).	Soft wire (annealed).
95	8 days.	3 minutes.
90	35 days.	5 minutes.
85	Unbroken at end of 16 mos.	1 day.
80	91 days.	266 days.
75	Unbroken.	17 days.
70		455 days.
65		455 days.
60	Unbroken.	Several years.

Soft irons and the "tin class" of metals and the woods are found to demand a higher factor of safety than hard iron. The elegant and valuable researches, also, of Mons. H. Tresca on the flow of solids,* and the illustrations of this action almost daily noticed by every engineer, seem to lend confirmation to the supposition of Vicat. The experimental researches of Prof. Joseph Henry, on the viscosity of materials, and which

* Sur l'Ecoulement des corps solides. Paris, 1869–72.

proved the possibility of the coexistence of strong cohesive forces with great fluidity,* long ago proved also the possibility of a behavior in solids, under the action of great force, analogous to that noted in more fluid substances.

On the other hand, the researches of the Author, indicating by strain-diagrams that the progress of this flow is often accompanied by increasing resistance, and the corroboratory evidence furnished by all such carefully made experiments on tensile resistance as those of King and Rodman, Kirkaldy and Styffe, have made it appear extremely doubtful whether hard iron is ever weakened by a continuance of any stress not originally capable of producing incipient rupture.

Kirkaldy concludes that the additional time occupied in testing certain specimens of which he determined the elongation "had no injurious effect in lessening the amount of breaking strain."† An examination of his tables shows those bars which were longest under strain to have had highest average resistance.

Wertheim supposed that greater resistance was offered to rapidly than to slowly produced rupture.

The experiments of the Author prove that, as had already been indicated by Kirkaldy, a lower resistance is offered by ordinary irons as the stress is more rapidly applied. This effect conspires with *vis viva* to produce rupture.

We conclude that the rapidity of action in cases of shock, and where materials sustain live loads, is a very important element in the determination of their resisting power, not only for the reason given already, but because the more rapidly common iron is ruptured the less is its resistance to fracture. This loss of resistance is about 15 per cent ‡ in some cases, noted by the Author, of moderately rapid distortion.

The cause of this action bears a close relation to that operating to produce the opposite phenomenon of the elevation of the elastic limit by prolonged stress, to be de-

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* Proc. Am. Phil. Society, 1844.

† Experiments on Wrought Iron and Steel, pp. 62, 83.

‡ Compare Kirkaldy, p. 83, where experiments which are possibly affected by the action of *vis viva* indicate a very similar effect.

scribed, and it may probably be simply another illustration of the effect of internal strain. Metals of the "tin class" exhibit, as has been shown by the Author,* an opposite effect. Rapidly broken, they offer greater resistance than to a static or slowly applied load. It has also been seen that annealed iron has, in some respects, similar qualities.

With a very slow distortion the "flow" already described occurs, and but a small amount of internal strain is produced, since, by the action noticed when left at rest, this strain relieves itself as rapidly as produced. A more rapid distortion produces internal stress more rapidly than relief can take place, and the more quickly it occurs the less thoroughly can it be relieved, and the more is the total resistance of the piece reduced. Evidence confirmatory of this explanation is found in the fact that bodies most homogeneous as to strain exhibit these effects least.

At extremely high velocities the most ductile substances exhibit similar behavior when fractured by shock or by a suddenly applied force, to substances which are really comparatively brittle.† In the production of this effect, which has been frequently observed in the fracture of iron, although the cause has not been recognized, the inertia of the mass attacked and the actual depreciation of resisting power just observed, conspire to produce results which would seem quite inexplicable, except for the evidently great concentration of energy here referred to, which, in consequence of this conspiring of inertia and resistance, brings the total effort upon a comparatively limited portion of the material, producing the short fracture, with its granular surfaces, which is the well-known characteristic of sudden rupture. Any cause acting to produce increased density, as reduction of temperature, evidently must intensify this action of suddenly applied stress.

The liability of machinery and structures to injury by shock is thus greatly increased, and it is quite uncertain what

* Trans. Am. Soc. C. E., 1874 *et seq.*

† Specimens from wrought-iron targets shattered by shock of heavy ordnance exhibit this change in a very unmistakable manner.

is the proper factor of safety to adopt in cases in which the shocks are very suddenly produced.

Meantime the precautions to be taken by the engineer are: To prevent the occurrence of shock as far as possible, and to use in endangered parts light and elastic members, composed of the most ductile materials available, giving them such forms and combinations as shall distribute the distortion as uniformly and as widely as possible.

The behavior of materials subjected to sudden strain is thus seen to be so considerably modified by both internal and external conditions which are themselves variable in character, that it may still prove quite difficult to obtain mathematical expressions for the laws governing them. An approximation, of sufficient accuracy for some cases which frequently arise in practice, may be obtained for the safety factor by a study and comparison of experimental results.

Egleston, studying the behavior of metal under long-continued and repeated stresses, finds evidence of the existence of a "law of fatigue and refreshment of metals," occurring as indicated by the Author. He also concludes* that metal once fatigued may sometimes be restored by rest or by heating that "the change produced is a chemical one," accompanied by "a change in the size, color, and surface of the grains of the iron or the steel." Surface injuries by blows were found to affect the metal, in some cases, to a depth of 15 millimetres (0.6 inch). He informs the Author that he finds evidence of the formation of crystals in the cold metal during the process of becoming fatigued, and a decided change in the proportion of combined and uncombined carbon.

The Effect of Repeated Variation of Load is most important. In the year 1859 Prof. Wöhler, in the employ of the German Government, undertook a series of experiments to determine the effect of prolonged varying stress on iron and steel. These experiments were continued until 1870. The apparatus used by Wöhler and his successor, Spangenberg, was of four kinds:

1. To produce rupture by repeated load.

* Transactions Institute Mining Engineers, 1880.

2. For repeated bending, in one direction, of prismatic rods.

3. For experiments on loaded rods under constant bending stress.

4. For torsion by repeated stress.

The amount of the imposed stress was determined by breaking several rods of like material, ascertaining the breaking load, and taking some fraction of this for the intermittent load.

From the results of these experiments of Wöhler, extending over eleven years, the observations here appended were deduced:

"WÖHLER'S LAW: *Rupture of material may be caused by repeated vibrations, none of which attain the absolute breaking limit. The differences of the limiting strains are sufficient for the rupture of the material.*"

The number of strains required for rupture increases much more rapidly than the weight of load diminishes.

The work of Wöhler and Spangenberg has proven what was long before supposed to be the fact—that the permanence and safety of any iron or steel structure depends not simply on the greatest magnitude of the load to be sustained, but on the frequency of its application and the range of variation of its amount. The structure or the machine must usually be designed to carry indefinitely whatever load it is intended to sustain and to be permanently safe, however much the stress may vary, or however frequent its application. The stress permitted and calculated upon must therefore be less as the variation is greater, and as the frequency of its application is greater. Although it is customary to make the working load one fifth or one sixth the maximum load that could be sustained without fracture, it has now become well known that this is not the correct method except for an unvarying load; although, as will be seen, these factors of safety are sufficient to cover the case studied by Wöhler.

Wöhler found that good wrought-iron and steel would bear loads indefinitely as follows:

	Lbs. per sq. in.	Kilogs. per sq. cm.
Wrought-iron, tension only........	+ 18,700 to + 30;	+ 1,309 to + 2.2
Wrought-iron, tension and compres.	+ 8,320 to − 8,320;	+ 582 to − 582
Cast-steel, tension only............	+ 34,307 to + 11,440;	+ 2,401 to + 801
Cast-steel, tension and compression	+ 12,480 to − 12,480;	+ 874 to − 874

Thus rupture is produced either by a certain load, called usually the "breaking load," once applied, or by a repeatedly applied smaller load. The differences of stresses applied, as well as their actual amount, determine the number of applications which may be made before fracture occurs, and the length of life of the member or the structure. This weakening of metal by repeated stresses is known as *fatigue*. It is not known that it may always be relieved, like internal stresses, by rest; but it is apparently capable of relief frequently by either simple rest for a considerable period, or by heating, working, and annealing.

The experiments described seem to indicate some relation between the action of variable loads and of prolonged stress where metals are soft enough to "flow."

Wöhler concluded that the allowable loads for the cases of stationary loading, loading in tension alternating with entire relief, and equal and alternate tensions and compressions, will be in the ratio 3 : 2 : 1.

The method above described is still in the experimental stage; but it may be provisionally accepted as safer than the usual method of covering cases of varying stresses by a factor of safety determined solely by custom or individual judgment. It has been the custom with some American bridge-builders to give members in alternate tension and compression a section equal to that calculated for a tension under static load equal to the sum of the two stresses—a rough method of meeting the most usual and serious case.

A number of engineers, commenting upon the work of Wöhler, Spangenberg, Weyrauch, and Launhardt, consider that the result is simply to base upon the ultimate strength a deduced limit of working stress which corresponds closely to the elastic limit, and generally urge that reasonable factors of

safety *related to the limit of elasticity* are preferable to the still uncertain method above described. It is admitted, however, that the results accord with those already indicated by experience where a definite practice has become settled upon.

There are many phenomena which cannot be conveniently exhibited by strain-diagrams; such are the molecular changes which occupy long periods of time. These phenomena, which consist in alterations of chemical constitution and molecular changes of structure, are not less important to the mechanic and the engineer than those already described. Requiring usually a considerable period of time for their production, they rarely attract attention, and it is only when the metal is finally inspected, after accidental or intentionally produced fracture, that these effects become observable. The first change to be referred to is that gradual and imperceptible one which, occupying months and years, and under the ordinary influence of the weather going on slowly but surely, results finally in important modification of the proportions of the chemical elements present, and in a consequent equally considerable change of the mechanical properties of the metal.

Exposure to the weather, while producing oxidation, has another important effect: It sometimes produces an actual improvement in the character of the metal. Old tools, which have been laid aside or lost for a long time, acquire exceptional excellence of quality. Razors which have lost their keenness and their temper recover when given time and opportunity to recuperate. A spring regains its tension when allowed to rest. Farmers leave their scythes exposed to the weather, sometimes from one season to another, and find their quality improved by it. Boiler-makers frequently search old boilers carefully, when reopened for repairs after a long period of service, to find any tools that have been lost and so improved.

36. A Method of Detecting any Overstrain to which a structure or either of its parts may have been subjected, which was devised, or more properly discovered, by the Author, is sometimes of service in revealing danger of accident, or the cause of disasters already arrived. It has been shown by the

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Author* and by other investigators, that when a metal is subjected to stress exceeding that required to strain it beyond its original apparent, or "primitive," elastic limit, this primitive elastic limit becomes elevated, and that strain-diagrams obtained autographically, or by carefully plotting the results of well-conducted tests of such metal, are "the *loci* of the successive limits of elasticity of the metal at the successive positions of set."†

It has been shown by the Author also that, at the successive positions of set, strain being intermitted, a new elastic limit is, on renewing the application of the distorting force, found to exist at a point which approximately measures the magnitude of the load at the moment of intermission.‡

Thus it is seen that a metal, once overstrained, carries permanently unmistakable evidence of the fact, and can be made to reveal the amount of such overstrain at any later time with a fair degree of accuracy. This evidence cannot be entirely destroyed, even by a moderate degree of annealing. Often, only annealing from a high heat, or reheating and reworking, can remove it absolutely. Thus, too, a boiler, or any structure, broken down by causes producing overstrain in its tension members, or in its transversely loaded beams (and, probably, in compression members—although the writer is not yet fully assured of the latter), retains in every piece a register of the maximum load to which that piece has ever been subjected; and the strain sheet of the structure, as strained at the instant of breaking down, can be thus laid down with a fair degree of certainty. The Author has found by subsequent tests that transverse strain produces the same effect upon the elastic limit for tension.

Here may be found a means of tracing the overstrains which have resulted in the destruction or the injury of any iron or steel structure, and of ascertaining the cause and the method of its failure, in cases frequently happening in which

* See Trans. Am. Soc. C. E., 1874 *et seq.*, Journal Franklin Institute, 1874; Van Nostrand's *Eclectic Engineering Magazine*, 1874, etc., etc.

† On the Strength, etc., of Materials of Construction, 1874, Sec. 20.

‡ On the Mechanical Treatment of Metals; *Metallurgical Review*, 1877; *Engineering and Mining Journal*, 1877.

they are indeterminable by any of the usual methods of investigation.

This method may thus sometimes be used to ascertain the probable cause of a boiler explosion, by determining whether the metal has been subjected to overstrain in consequence of overpressure. The causes of accidents to machinery may also be thus detected, and many other applications might be suggested.

37. **The Effect of Temperature and its Variation** on iron and steel is probably the most important of all those phenomena which modify the behavior of iron or steel under load.

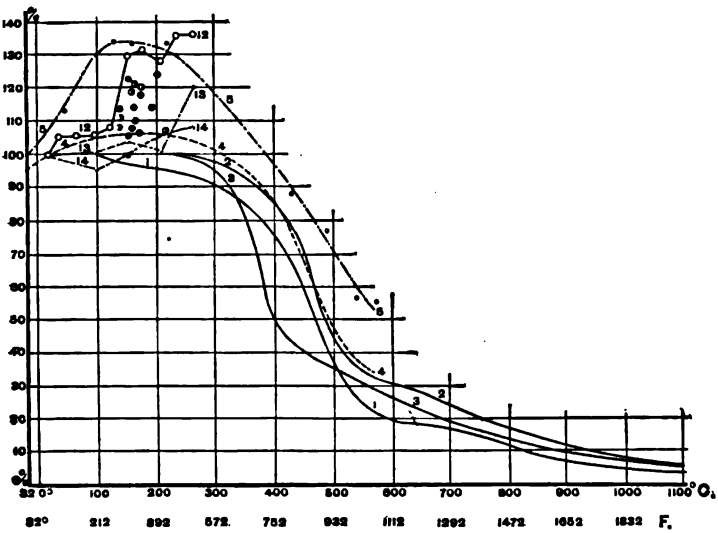

FIG. 53.—HEAT *vs.* TENACITY.

The diagram above* graphically represents the results of several series of experiments.

Curves Nos. 1 and 2 represent Kollmann's experiments on iron, and 3 on Bessemer "steel." No. 1 is ordinary, and 2 steely puddled iron.

Curve No. 4 represents the work of the Franklin Institute on wrought-iron.

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* Eisen und Stahl, A. Martens; Zeitschrift des Vereins Deutscher Ingenieure; Feb. 1883, p. 127.

Curve No. 5 gives Fairbairn's results, working on English wrought-irons.

Nos. 6 to 11 are Styffe's, and represent the experiments made by him on Swedish iron. The numbers do not appear, as these results do not fall into curves; these results are indicated by circles, each group being identified by the peculiar filling of the circles, as one set by a line crossing the centre, another by one across, a third by a full circle, etc.

The broken lines, 12 and 13, are British Admiralty experiments on blacksmiths' irons, and No. 14 on Siemens steel.

The first five series only are of value as indicating any law; and they exhibit plainly the general tendency already referred to, to a decrease of tenacity with increase of temperature.

Fairbairn's experiments, No. 5, best exhibit the maximum, first noted by the Committee of the Franklin Institute, at a temperature between that of boiling water and the red heat.

It will be observed that the measure of tenacity, at the left, is obtained by making the maximum of Kollmann unity. It will also be noted that Kollmann does not find a maximum as in curves 4 and 5, but, on the contrary, a more rapid reduction in strength at that temperature than beyond.

It would seem, therefore, that that peculiar phenomenon must be due to some accidental quality of the iron.* The Author has attributed it to the existence in the iron, before test, of internal stresses which were relieved by flow as the metal was heated, disappearing at a temperature of 300° or 400° Fahr. (149° to 204° Cent.).

The experiments of Mr. Oliver Williams † in determining the change produced in the character of the fracture of iron by transverse strain, at extreme temperatures, indicate loss of ductility at *low* temperatures.

Two specimens of nut-iron, from different bars, made at Catasauqua, Pennsylvania, were first nicked with a cleft on one side only, and then broken under a hammer, at a temperature

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* Isherwood suggests that this is simply due to repeatedly breaking the same piece.

† *The Iron Age*, New York, March 13, 1873, p. 16.

of about 20° Fahr. (— 7° Cent.). At this temperature both specimens broke off short, showing a clearly defined granular or steely iron fracture. The pieces were then gradually heated to about 75° Fahr. (24° Cent.), and then broken as before, developing a fine, clear, fibrous grain. The two fractures were

FIG. 54.—FRACTURE AT ORDINARY TEMPERATURE.

but four inches (10.16 centimetres) apart, and are entirely different. The accompanying illustrations, from the Author's collection, exhibit this case.

It has been long known that a granular fracture may be produced by a shock, in iron which appears fibrous when gradually torn apart. This was fully proven by Kirkaldy.* Mr. Williams was, probably, the first to make the experiment just described, and thus to make a direct comparison of the characteristics of fracture in the same iron at different temperatures.

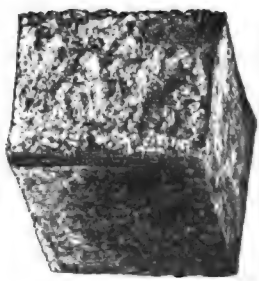

FIG. 55.—FRACTURE AT LOW TEMPERATURE.

Valton has found † that some iron becomes brittle at temperatures of 572° or 752° Fahr. (300° to 400° Cent.), and regains ductility and toughness at higher temperatures. On the whole, the frac-

* Experiments on Iron and Steel.

† Bulletin Iron and Steel Assoc., Feb. 1877.

ture of iron at low temperatures has been found to be characteristic of a brittle material, while at higher temperatures it exhibits the appearance peculiar to ductile and somewhat viscous substances. The metal breaks, in the first case, with slight permanent set and a short granular fracture, and in the latter with, frequently, a considerable set, and the form of fracture indicating great ductility. The variation in the behavior of iron, as it approaches the welding heat, illustrates the latter condition in the most complete manner.

Valton found that a steel rod bent very well at a temperature a little below dull red, but broke at a temperature which may be called blue, the fracture showing that color. Portions of the rod which were below this temperature manifested much toughness, and bent without fracture. Charcoal pig-iron from Tagilsk, made in 1770, irons obtained from the Ural in rods and sheets, soft Bessemer and Martin steels from Terrenoire, soft English steel and good English merchant-bars, all gave the same results, whether the metal tested had been hammered or rolled. Valton found that the phenomenon had been long known to the workmen under his direction. In working sheet-iron with the hammer they wait until the metal has cooled further when approaching the temperature which would give the blue fracture when broken. He concludes that wrought-irons, as well as some kinds of soft steel, even when of excellent quality, are very brittle at a temperature a little below dull red heat—577° to 752° Fahr. (between 300° and 400° Cent.).

The variation of strength follows quite closely the change of density, which latter is illustrated in the preceding diagram, which exhibits increase of volume from the freezing-point.

The sudden fall of the line before reaching the melting-point indicates the sudden increase of volume which castings exhibit while cooling, and which enables "sharp" castings to be secured. It is at the crest noted near this point that viscosity is observed. From this point back to the freezing-point the variation follows a regular law.

It would thus seem that the general effect of increase or decrease of temperature is, with solid bodies, to decrease or increase their power of resistance to rupture, or to change of

form, and their capability of sustaining "dead" loads; and we may conclude:

(1) That the general effect of change of temperature is to produce change of ductility, and consequently change of resilience, or power of resisting shocks and of carrying "live loads." This change is usually opposite in direction and greater in degree at ordinary temperatures than the variation simultaneously occurring in tenacity.

(2) That marked exceptions to this general law have been noted, but that it seems invariably the fact that, wherever an exception is observed in the influence upon tenacity, an exception may also be detected in the effect upon resilience. Causes which produce increase of strength seem also to produce a simultaneous decrease of ductility, and *vice versa*.

(3) That experiments upon copper, so far as they have been carried, indicate that (as to tenacity) the general law holds good with that metal.

(4) That iron exhibits marked deviations from the law between ordinary temperatures and a point somewhere between 500° and 600° Fahr. (260° and 316° Cent.), the strength increasing between these limits to the extent of about 15 per cent with good iron. The variation becomes more marked and the results more irregular as the metal is more impure.

(5) That above 600° Fahr. (316° Cent.) and below 70° (21° Cent.) the general law holds good for iron, its tenacity increasing with diminishing temperature below the latter point at the rate of from 0.02 to 0.03 per cent for each degree Fahrenheit, while its resilience decreases in an undetermined ratio for good iron, and to the extent of reduction to one third its ordinary value or less, at 10° Fahr. (— 12° Cent.) when cold-short, and in the latter case the set may be less than one fourth that noted at a temperature of 84° Fahr. (29° Cent.).

(6) That the viscosity, ductility, and resilience of metals are determined by identical conditions, and that the fracture of iron at low temperatures has accordingly been found to be characteristic of a brittle material, while at the higher temperatures it exhibits the appearance peculiar to ductile and somewhat viscous substances. The metal breaks in the first case

with slight permanent set and a short granular fracture, and in the latter with frequently a considerable set and a form of fracture indicating great ductility. The variation in the behavior of iron, as it approaches a welding heat, illustrates the latter condition in the most complete manner.

(7) That the precise action of the elements with which iron is liable to be contaminated, and the extent to which they modify its behavior under varying temperature, remain to be fully investigated, but that the presence of phosphorus and of other substances producing "cold-shortness," exaggerates to a great degree the effects of low temperature in producing loss of toughness and resilience.

(8) That the modifications of the general law with other metals than iron and copper, and in the case of alloys, have not been studied, and are entirely unknown.

The practical result of the whole investigation is that iron and steel, and probably other metals, do not lose their power of sustaining absolutely "dead" loads at low temperatures, but that they do lose, to a very serious extent, their power of sustaining shocks or of resisting sharp blows, and that the factors of safety in structures need not be increased in the former case, where exposure to severe cold is apprehended; but that machinery, rails, and other constructions which are to resist shocks should have larger factors of safety, and should be most carefully protected, if possible, from extreme temperatures.

The Stress Produced by Change of Temperature is easily calculated when the modulus of elasticity and the coefficient of expansion are known, thus:

Let E = the modulus of elasticity;
λ = the change of length per degree and per unit of length;
Δt° = the difference of initial and final temperatures;
p = the stress produced.

Then

$$p : E :: \lambda \Delta t^\circ : 1,$$

$$\therefore p = \lambda E \Delta t^\circ. \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (1)$$

For good wrought-iron and steel, taking E as 28,000,000 pounds on the square inch, or 2,000,000 kilogrammes on the square centimetre, and λ as 0.0000068 for Fahrenheit, and as 0.0000120 for Centigrade degrees:

$$\left.\begin{aligned} p &= 190 \Delta t^\circ \text{ Fahr., nearly,} \\ &= \ \ 25 \Delta t^\circ \text{ Cent., nearly.} \end{aligned}\right\} \quad . \quad . \quad . \quad . \quad . \quad (2)$$

For cast-iron, taking $E = 16{,}000{,}000$; $\lambda = 0.0000062$:

$$\left.\begin{aligned} p &= 100 \Delta t^\circ \text{ Fahr., nearly,} \\ &= \ \ 12 \Delta t^\circ \text{ Cent., nearly.} \end{aligned}\right\} \quad . \quad . \quad . \quad . \quad . \quad (3)$$

This force must be allowed for as if a part of the tension, T, or compression, C, produced by the working load when the parts are not free to expand.

Sudden Variation of Temperature has an effect upon steel which is very great when the proportion of carbon is not far from one per cent. With less carbon the effect is less observable, and with the wrought-irons and with ingot metals containing less than one third per cent carbon and other hardening elements, it becomes quite unimportant. Soft irons are still further softened by sudden reduction of temperature from the red heat. Cast-irons, unless of the class known as "chilling irons," are much less affected than steel, and when very rich in graphitic carbon are not perceptibly hardened.

When either iron or steel is repeatedly heated and cooled, a permanent change of form takes place. Colonel Clarke has shown* that cylinders repeatedly heated to a high temperature and suddenly cooled, become enlarged in diameter permanently. Pieces of tempered steel are larger than when untempered.

Cast-iron ordnance, after having been discharged many times, becomes unsafe in consequence of weakening, which is

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* *Philosophical Magazine*, 1863.

probably principally due to strains caused by sudden and irregular changes of temperature in service.

Such grades of steel as take a temper are greatly strengthened unless too highly hardened, in which case they become brittle from internal stresses. The Author has found tempering in mercury to increase greatly both the strength and the toughness of small pieces of good tool steel. Kirkaldy has found, by an extended series of experiments, that tempering tool steels in oil greatly increases both strength and elasticity, while hardening in water reduces both. The higher the temperature at which, without risk, the steel can be cooled, the greater is this increase of strength. Hard steels exhibit the fact better than soft steels. Dividing steels into series in the order of their contents in carbon, beginning with the softest grades, the following were the percentages of increase of strength from weakest to strongest: 11.8, 24.2, 40.7, 53.2, 57.0, 64.1, 70.9, 77.6. The harder steels were highly heated; the soft steels only moderately.

A singular change is observed in iron and in the soft steels, and may perhaps be found to occur with other metals, when the temperature approaches what is known as the black heat—a temperature not far from 600° or 700° F. (316° to 370° C.), and below a red-heat visible in the dark. At this temperature, metal which bends readily either cold or at the full red heat is found to be exceedingly brittle and to break easily, especially under percussion, without bending. This heat with its peculiar effect may be reached in a bath of boiling tallow at a little above the lower temperature above specified. The steels show less of this effect, usually, than the irons. The presence of more than a trace of sulphur, or phosphorus, or of other hardening elements, exaggerates this action.

38. **Crystallization and Granulation** are the two methods of alteration of molecular structure which are consequent upon the action of any cause which continually separates the particles of the metal beyond the range marked and limited by the elastic limit. No evidence is to be found that a single suddenly applied force, producing fracture, may cause such a systematic and complete rearrangement of molecules. The

granular fracture produced by sudden breaking, and the crystalline structure produced as above during long periods of time, are apparently as distinct in nature as they are in their causes. But simple tremor, ***where no sets of particles are separated so far as to exceed the elastic range***, and to pass beyond the limit of elasticity, does not seem to produce such changes. In fact, some of the most striking illustrations of the improvement in the quality of wrought-iron with time have occurred where severe jarring and tremor were common. Metal has been subjected for many years to the strains and tremor accompanying the passage of trains without apparent tendency to crystallization, and with evident improvement in its quality.

Wöhler found cubic crystals in cast-iron plates which had been for some time kept at nearly the temperature of fusion in a furnace, and Augustine found similar crystals in gun-barrels: Percy found octahedra of considerable size in a bar which had been used in the melting-pot of a glass-furnace. Fairbairn asserts the occasional occurrence of such change due to shock, jar, and long-continued vibration. Miller found cubic crystallization plainly exhibited in Bessemer iron, which may, however, have been due to the presence of manganese. Hill shows * that heat may produce such crystallization.

In a discussion which took place many years ago before the British Institution of Civil Engineers, Mr. J. E. McConnell produced a specimen of an axle which he thought furnished nearly incontestable evidence of crystallization. One portion of this axle was clearly of fibrous iron, but the other end broke off as short as glass. The axle was hammered under a steam hammer, then heated again and allowed to cool, after which it was found necessary to cut it almost half through and hammer it for a long time before it could be broken. The great testing-machine at the Washington Navy Yard has a capacity of about 300 tons, and has been in use 40 years. Commander Beardslee subjected it to a stress of 288,000 lbs. (130,000 kilogrammes), which stress had frequently been approached before; but it subsequently broke down under about 100 tons. The connect-

* *Iron Age*, 1882; *Mechanics*, 1882.

ing-bar which gave way had a diameter of five inches, and should have originally had a strength of about 400 tons (406,400 kilogrammes). Examining it after rupture, the fractured section was found to exhibit strata of varying thickness, each having a characteristic form of break. Some were quite granular in appearance, but the larger proportion were distinctly crystalline. Some of these crystals are large and well defined. The laminæ, or strata, preserve their characteristic peculiarities, whether of granulation or of crystallization, lying parallel to their axis and extending from the point of original fracture to a section about a foot distant, where the bar was broken a second time (and purposely) under a steam hammer. It thus differs from the granular structure which distinguishes the surfaces of a fracture suddenly produced by a single shock, and which is so generally confounded with real crystallizion.

39. **Irons and Steels Compared** with reference to their composition and qualities, even when the latter are given as much of the character of the best iron as is possible, will exhibit some marked differences.

In composition the following may be considered good representative examples:

	Irons.			Steels.	
	Swedish.	Dartmoor.	Pennsylvania.	"Mild."	Very "Mild."
Carbon	0.087	0.016	0.067	0.238	0.009
Silicon	0.056	0.022	0.020	0.105	0.163
Sulphur	0.005	0.104	0.001	0.012	0.009
Phosphorus	.....	0.106	0.075	0.034	0.084
Manganese	.....	0.280	0.009	0.184	0.620
Iron by diff.	99.220	99.372	99.828	99.427	99.115
	100.000	100.000	100.000	100.000	100.000

All the hardening elements usually appear in larger proportion in the steels than in the irons; but this is not invariably the fact, especially with those very mild steels which can be made by the crucible process.

Comparing the analyses of the two classes of metal, it will be found that the best irons are more irregular and uncertain

in composition than the best steels; that they contain considerable amounts of cinder, or slag, derived from the puddle-ball and the crude cast-iron from which it is made; that the carbon and silicon are usually less in quantity, though very variable; sulphur and phosphorus are commonly "higher" than in steels; and the whole list of elements, aggregating, slag aside, less in the irons than in the steels, varies greatly in proportions, and by no law. The steels are capable of more exact prescription of constitution than irons, and are especially distinguished by their richness in manganese, silicon, and carbon, and their freedom from slag and from sulphur and phosphorus. The crucible steels contain, as a rule, much less manganese and silicon than do the others. For boiler-plate, the carbon should be kept below one fourth of one per cent, and all other elements as low as possible; but the effect of manganese and other hardening constituents is not sufficiently well settled, especially where the metal is exposed to the action of the fire, and to varying temperatures generally, to admit of the prescription of a formula for the best possible composition.

Comparing the structure of iron and steel, it will be found that the latter is comparatively, often almost absolutely, homogeneous; while the former is very irregularly laminated, and exhibits the most remarkable fibrous texture when broken slowly, the slag separating threads of metal by encasing them in sheaths of mineral, and layers of cinder and oxide causing stratification by preventing the welding of the sheets of thinner iron of which the plate is made. The whole structure of the "pile" from which it is rolled is reproduced in a distorted fashion in the finished plates. The steel breaks with the same fracture, and offers the same resistance in both directions; while iron, especially the cheaper grades, usually resists longitudinal forces much better than transverse.

In tenacity the best steel boiler-plate is but little, if any, stronger than the best boiler-iron: it excels the latter, however, in ductility as well as in homogeneousness, and resists the corroding action of the fluids with which it is brought in contact much better than iron. If too rich in manganese, too high in carbon or silicon, or if it contains an appreciable amount of

phosphorus, steel becomes unreliable, and more dangerous than ordinary irons.

"*Mild Steel*" will take a temper, often, when containing over 0.30 per cent of carbon. Its uniformity and reliability decrease as its strength and hardness increase, and also with increase of thickness and size of the mass produced. This fact has caused the British Lloyds regulations to make the following allowances:

Plates and stays 0 to 1 inch thick, maximum tensile strength 67,200 pounds (4724 kgs. per sq. cm.).

Plates and stays 1 to $1\frac{3}{8}$ inches thick, maximum tensile strength 64,960 pounds (4567 kgs. per sq. cm.).

Plates and stays over $1\frac{3}{8}$ inches thick, maximum tensile strength 62,720 pounds (4410 kgs. per sq. cm.).

The same proportions carried further would reduce the allowable tenacity of steel in heavy and thick masses to that of good iron, leaving its homogeneousness the only advantage.

If used at all, the harder steels should be tempered in oil; but they have no place in boiler-construction.

The conclusions to be to-day reached after comparing steel and iron as materials for boiler-construction, and in view of experience to date in their use, are fully confirmatory of the assertion of the late Mr. A. L. Holley, written a generation ago:* "It appears extremely probable that this material" (steel) "will gradually come into exclusive service, not only increasing the safety and decreasing the repair expense of boilers, but promoting the economy of steam generation and of railway working generally."

40. **The Characteristics of Iron Plate** used in boiler-making must all be in accordance with the requirements already stated. A number of different qualities of both iron and steel are sent into the market for use in boiler-construction. Of these the makes and qualities of iron have been long well settled; but the best qualities and compositions of steel are not as well established. No hard steels, however, are classed as boiler-steels.

Good Boiler-plate is commonly assumed to be made of

* American and European R ilway Practice, p. 29.

"charcoal iron," i.e., of iron made from pig-iron produced in the charcoal blast-furnace, no other fuel than wood-charcoal being used. The scarcity of charcoal and the cost of such irons is gradually making it more and more difficult to secure them. American boiler-plate is classed by the following-named brands:

"Charcoal No. 1 iron" (*C.* No. 1) is made entirely of charcoal iron; it has a tenacity exceeding 40,000 pounds per square inch (2812 kgs. per sq. cm.), is hard, but not very ductile, and is never used when flanging or considerable change of form is required, as it is apt to break at the bend. When reheated and reworked to form what is called "charcoal No. 1 reheated iron" (*C.* No. 1, *R. H.*) it becomes still harder, and is found to wear well in fireboxes, but is still less well fitted than before for flanging and working, on account of its increased brittleness.

"Charcoal Hammered No. 1 Shell-iron" (*C. H.* No. 1, *S.*) is a better worked iron than *C.* No. 1; but it is not always hammered. It is stronger, having a tenacity of 50,000 to 55,000 pounds per square inch (3515 kgs. per sq. cm. to 3838) in the direction of the fibre, and seventy-five or eighty per cent of this amount across the grain. This grade is not usually flanged, but may be bent if handled with care, and if the radius of curvature is made sufficiently great; it is sold principally for use in the shells of boilers. A better quality known as "flange-iron" (*C. H.* No. 1, *F.*) is much more ductile, and may be worked into flanged sheets; it is nearly equally strong in both directions, and has about the tenacity of the preceding. A still harder grade of hammered iron is intended for fireboxes mainly (*C. H.* No. 1, *F. B.*), and especially for flue-sheets, which are flanged to receive the flues; and a still better grade (*C. H.* No. 1, *F. F. B.*) called "charcoal hammered No. 1, flange firebox" iron, extra firebox, or, sometimes, best firebox, is made, which is more generally considered best for this use.

All the grades of charcoal-irons have been made principally in Pennsylvania.

"Shell" boiler-plate has often, if not generally, an outer skin of charcoal-iron, the "pile" from which it is rolled being composed of other irons, and covered top and bottom with

pieces of charcoal-iron. Although distinctively made for the shell of the boiler, the best makers usually prefer to use better grades for that purpose.

"*Refined*" *Iron* is used for miscellaneous purposes when strength and toughness are not specially demanded, and where no risks are involved. It is not intended for boiler-making; it is made directly from the pig-iron. "Tank" iron is a still cheaper grade, used only for the most unimportant purposes. Neither of these grades should be used in boilers, or in any structure of great magnitude or value.

The best British boiler and smith's irons are made in Yorkshire, the best known in the United States being those from the Low Moor, the Bowling, and the Farnley works, and sold in the trade as "best Yorkshire" irons.

41. **The Manufacture of Boiler-plate,** iron or steel, is not essentially different in method from the making of other iron and steel "uses." Iron boiler-plate is made from puddled or scrap iron, the process of puddling being always that which is resorted to in the reduction of the carbon and the production of the wrought-iron from the cast. In the rolling of plates, the wrought-iron, in bars, slabs, or miscellaneous scrap, is formed into "piles" of the proper size and form, which, after being heated to a full welding temperature, are passed through a heavy roll-train of sufficient size and power to weld the constituent pieces into a comparatively solid mass, and to reduce that mass to the desired thickness. The pile is made of such size and shape as may be found to give the proper form and dimensions of sheet.

Steel plate is oftenest produced by the Siemens-Martin process of reduction of cast with wrought iron of selected qualities, in the "open-hearth" or Siemens regenerative furnace, securing freedom from cinder by stirring, and from oxide by the addition of manganese in the form either of spiegeleisen for hard or of ferro-manganese for soft steels, and then, while still very fluid, tapping into the ingot-mould, whence the ingot, when sufficiently cooled, is taken to be rolled into plate. An intermediate reheating of the ingot, or a period of "soaking" in hot "soaking-pits," is very generally found advisable to secure

a comparative uniformity of temperature throughout the ingot, in order that it may be successfully rolled.

The Bessemer process produces "steel," or more correctly "ingot-iron," boiler-plate by a very similar series of chemical operations; but it usually deals with larger masses, and furnishes, as a rule, harder steels. The rolling of steel demands the use of more powerful roll-trains than are needed in rolling iron.

Comparing the two processes, it is seen that the wrought-iron plate must necessarily retain some of the slag which came into it from the puddle-ball, and that it must be liable to defects in welding where the several pieces of which the pile is composed come together, especially should those surfaces be covered, as is often the case, with a heavy coating of oxide. Iron plate must thus always exhibit some defect of homogeneousness, and may be seriously defective in consequence of "lamination" produced as just described. On the other hand, steel, whether made by the crucible, the Bessemer, or the Siemens-Martin process, is always very uniform in texture, and is usually so in composition. The molten mass allows all slag and oxide to rise to its surface, and thus the fibrous and laminar character of iron is avoided, while the subsequent processes do not involve necessity of welding part to part. It thus happens that while iron boiler-plate is a mass of heterogeneous constituent elements, and liable to a thousand defects, steel is equally remarkable for its unity, homogeneousness, and reliability.

When an iron surface, parallel to the line of direction of rolling of plates, or of drawing down of pieces made or shaped under the hammer, is etched, it exhibits plainly the lines of "fibre" produced by the drawing out of the cinder originally present in the puddle-ball, and reveals any defective weld or the presence of any mass of foreign material. When a cross-section is made, as in the cases exhibited in the preceding figures, the character of the piling is shown, and also that of the workmanship. In these examples, which are reduced to one half the size of the originals, Fig. 56 is a section so etched of an iron locomotive axle, and Fig. 57 of a steel axle of similar

size and design. The beautiful homogeneousness of good steel is exhibited by the almost perfect uniformity of the color and texture of the surface; while the irregularity both of color and structure of the other illustration reveals plainly the reasons for the variable wearing quality and the inevitable uncertainty of strength which must always attend the use of forged iron, and especially when made of "scrap." It is evidently hope-

FIG. 56.—LOCOMOTIVE AXLE—"SPECIAL" IRON.

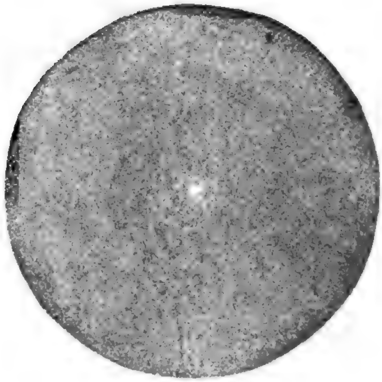

FIG. 57.—LOCOMOTIVE AXLE—STEEL.

less to secure perfect uniformity of structure, texture, and strength, or even to obtain soundness, where such great numbers of welds are to be made, and where so much impure and foreign material is distributed, hap-hazard, through the mass.

42. The Methods of Test of iron and steel, relied upon to reveal the properties and quality of the metal, are becoming well understood and standardized, and are universally practised in all important work by experienced and skilful engineers.

Testing Machines are used for testing small sections and pieces of moderate length. They are usually built by manufacturers who make a business of supplying them to engineers and other purchasers, and are generally made of several standard sizes. The machine is frequently fitted up to test both longitudinally and transversely; although the tests generally made are in but one direction. The Author has been accustomed to keep in use a machine specially intended to test in

tension and compression, and also separate machines for transverse and torsional tests. *Tension-machine* is shown in Fig. 58: it consists of two strong cast-iron columns, secured to a massive bed-frame of the same material; above these columns is fastened a heavy cross-piece, also of cast-iron, containing two sockets, in which rest the knife-edges of a large scale-beam. The upper chuck is suspended by eye-rods from knife-edges. All the knife-edges are tempered steel, and the sockets and

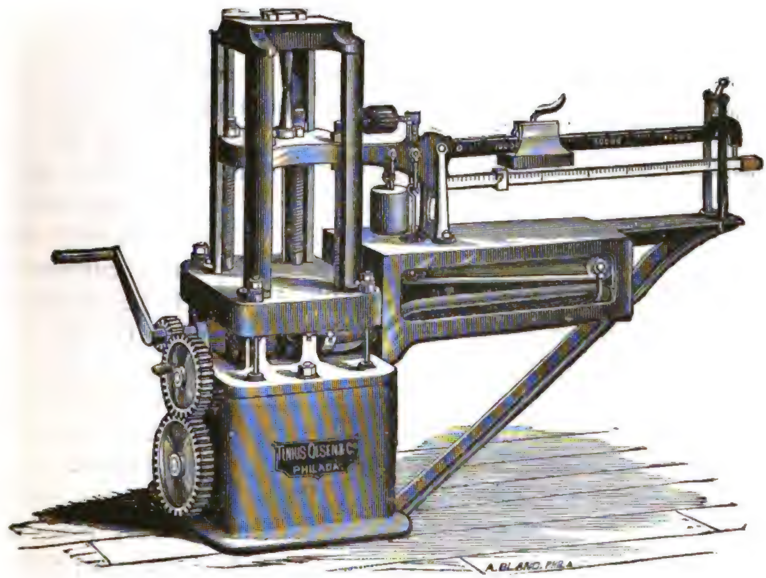

FIG. 58.—TENSION TESTING-MACHINE.

eyes are lined with the same material, thus reducing friction to a minimum. The load is applied by means of a screw, or by the hydraulic press, with a fixed plunger and movable cylinder. The stress to which the test-piece is subjected is measured by means of suspended weights and a sliding poise. The specimen is secured in the chucks either by wedge-jaws or bored chucks.

The extensions are measured by means of an instrument (Fig. 59) in which contact is indicated by an "electric contact apparatus." This instrument consists of two accurately made

micrometer screws, working snugly in nuts secured in a frame which is fastened to the head of the specimen by a screw clamp. It is so shaped that the micrometer screws run parallel to and equidistant from the neck of the specimen on opposite sides. A similar frame is clamped to the lower head of the specimen, and from it project two insulated metallic points, each opposite one of the micrometer screws. Electric connection is made between the two insulated points and one pole of a voltaic cell, and also between the micrometer screws and the other pole. As soon as one of the micrometer screws is brought in contact with the opposite insulated point a current is established, which fact is immediately revealed by the stroke of an electric bell placed in the circuit. The pitch of the screws is 0.02 of an inch (0.508 mm.), and their heads are divided into 200 equal parts; hence a rotary advance of one division on the screw-head produces a linear advance of one ten-thousandth (0.0001) of an inch (0.00254 mm.).

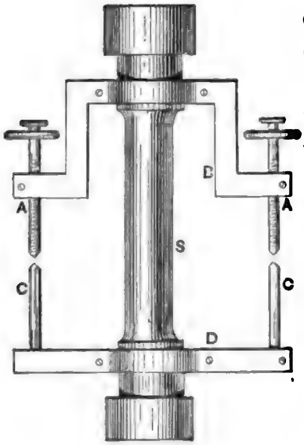

FIG. 59.—MEASURING INSTRUMENT.

A vertical scale, divided into fiftieths of an inch (0.508 mm.), is fastened to the frame of the instrument, set very close to each screw-head and parallel to the axis of the screw; these serve to mark the starting of the former, and also to indicate the number of revolutions made. By means of this double instrument the extensions can be measured with great certainty and precision, and irregularities in the structure of the material, causing one side of the specimen to stretch more rapidly than the other, do not diminish the accuracy of the measurements, since half the sum of the extensions indicated by the two screws is always the true extension caused by the respective loads.

The use of the hydraulic press is occasionally found to bring with it some disadvantages. The leakage of the press or of the pump is itself objectionable, and, where leakage occurs, it is difficult to retain the stress at a fixed amount during the time

required in the measurement of extensions. In such cases absolute rigidity in the machine is important, and the stress should be applied by mechanism, which usually consists of a train of gearing operated by hand or by power transmitted from some prime mover, and itself operating a pulling or compressing screw, as in Fig. 56.

The "Autographic" Testing-Machine devised by the Author is used where it is desired to obtain a knowledge of the general character of the metal, including its elasticity and resilience, and the method of variation of its normal series of elastic limits, and where a permanent graphical record is found useful. It is shown in the accompanying figure.

Fig. 61 is a perspective view of this machine. It consists of two A-shaped frames firmly mounted on a heavy bed-plate. The frames are secured to each other by cross-bolts. Near the top of each of these frames are spindles, each of which has a head with a slot or jaw to receive and hold the square heads of the specimens. The two spindles are not connected to each other in any way, excepting by the specimen which is placed in the jaws to be tested. To one spindle a long arm is attached, which carries a heavy weight at the lower end. The other has a worm-gear wheel attached to its outer end. This wheel is driven by a worm on the shaft which is turned by a hand crank. When a specimen is placed in the two jaws, and the spindle is turned by the worm-gear, the effect is to twist the specimen which would turn the spindle; but in order to do this the weight on the end of the arm must be swung in the direction in which the specimen is twisted. But the farther the arm is moved from a vertical position, the greater will be the resistance of the weight to the turning of the shaft, while the movement of the arm and weight is effected by the force exerted through the specimen so that the position of the arm and weight will at all times give a measure of the torsional stress, which is exerted on the specimen by the one spindle, and transmitted by the former to the other spindle.

But as this torsional stress which is exerted on the specimen is increased, it will at once commence to "give way," or be twisted more or less by the stress according to the quality of

the material. In making such torsional tests, it is essential that we should know how much the specimen was twisted, as the strains to which it was subjected were increased. If we could procure a record of this, it would be an indication of the capacity of the material to resist such stresses, or, in other words, of its quality. The testing-machine which has been described was designed by the Author for this purpose. The record is made in the following way: To one spindle a cylindrical drum is attached, which is covered with a suitable sheet of paper. To the pendulum, is attached a pencil, the point of which bears on the paper on the drum. Now supposing that the specimen in the machine should offer no resistance, but should merely twist, the pencil would then remain stationary, and as the drum is revolved the pencil would trace a straight line on

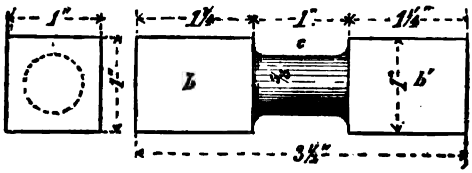

FIG. 60.—TEST-PIECE.

the paper, the length of which line would measure the amount by which the specimen was twisted. If, on the other hand, a specimen be supposed to resist and to twist simultaneously, as is always the case, then it will presently be seen that the spindle would be turned, and the arm with the weight would be moved from a vertical position a distance proportional to the strain resisted by the specimen. The pencil-holder, being attached to the arm, would move with it. As explained before, the distance which the arm and its weight are moved from a vertical position indicates the stress on the specimen. Next, in order to make a record of this distance, a "guide-curve" is attached to the frame of the machine, so that when the pencil-holder is moved out of the vertical position the pencil is moved toward the left by the guide-curve, which is of such a form that the lateral movement which it gives to the pencil is proportional to the moment of the weight on the end

of the arm. Now suppose, if such a thing were possible, that a specimen were tested which would not "give" or twist at all: in that case the spindles, the drum, and the pencil would turn together, or their movements would be simultaneous, so that the pencil would draw a vertical line along the paper. But

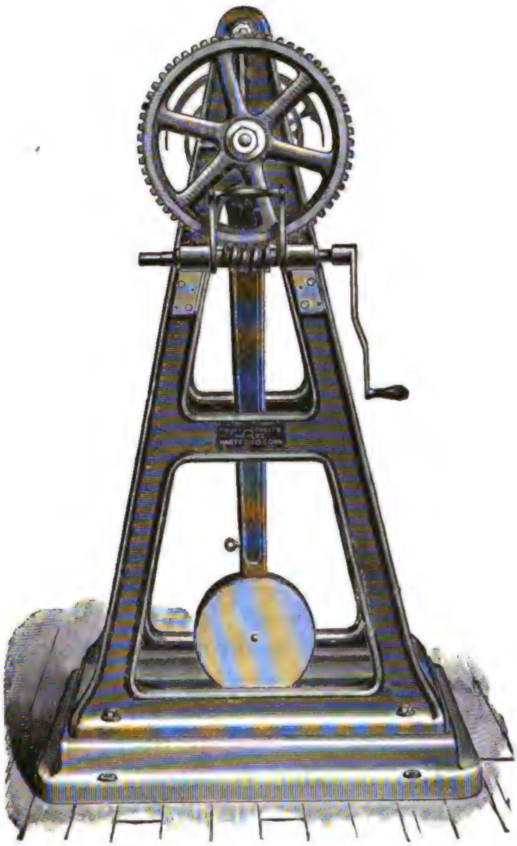

FIG. 61.—AUTOGRAPHIC MACHINE.

there is no material known which would not yield or twist more or less, so that the pencil will always draw some form of curved line, which indicates the quality of the material tested. The test-pieces are held in a central position in the jaws by lathe "centres," which are placed in suitable holes drilled in the

spindles for that purpose. The specimen is then held securely by wedges. In the diagrams each inch of ordinate denotes 100 foot-pounds of moment transmitted through the test-piece, and each inch of abscissa indicates 10 degrees of torsion. The friction of the machine is not recorded, but is determined when the machine is standardized, and is added in calculating the results.

By the use of this machine the metal tested is compelled to tell its own story, and to give a permanent record and graphical representation of its strength, elasticity, and every other quality which is brought into play during its test, and thus to exhibit all its characteristic peculiarities.

The figures on page 105 are derived from a test by tension, as made for the Author. On page 106 is given the record of a test of steel made by the Ordnance Department, U. S. A.

43. **Tests of Strength and Ductility** of irons and steels have now been made in such numbers, and with such a variety of composition, that the engineer designing or constructing boilers need have no doubt in regard to the character of the metal to be incorporated in the structure.

The mean of a considerable number of experiments on excellent American iron boiler-plate, made under the eye of the Author, gave a tenacity of 54,000 pounds per square inch (3795.2 kilogs. per sq. cm.) with a variation of 9 per cent; flange-iron averaged but 42,000 pounds (2952.6 kgs. per sq. cm.) with a variation of nearly 40 per cent; the highest-priced, and presumably best, plate in the market averaged very nearly 60,000 pounds (4218 kgs.), varying 14 per cent; and common tank-iron showed practically the same tenacity and variation as the flange-iron, and less ductility. Thoroughly good Pennsylvania plate, in other experiments, gave, for all good grades, tenacities not ranging much from 55,000 pounds per square inch (3866.5 kilogs. per sq. cm.), and an elastic limit at 60 per cent of the ultimate strength. Such tenacity is not usually to be expected when buying in the market, and it is very common, when designing boilers the material of which is not prescribed, for the designer to assume that its tenacity may not exceed 40,000 pounds (2812 kgs.). On the other hand, a contract and specification prescribing careful test may some-

TEST OF WROUGHT-IRON; LENGTH 8″ (19.32 cm.), DIAM. 0.798″ (2.03 cm.).

Loads.		Micrometer Readings.		Extensions.		Sets.	
Actual.	Per sq. in.			Actual.	Per cent.	Actual.	Per cent.
150	.....	.6600	.7913	.....	....	....	....
2,000	4,000	.6628	.7910	.0013	.016	....	....
4,000	8,000	.6637	.7922	.0023	.029	....	....
6,000	12,000	.6646	.7930	.0035	.044	....	....
8,000	16,000	.6606	.7946	.0050	.063	....	....
10,000	20,000	.6630	.7948	.0058	.073	....	....
150	....	.6600	.7914	.....	....	.0001	.001
11,000	22,000	.6639	.7951	.0064	.030	....	....
12,000	24,000	.6700	.7953	.0070	.037	....	....
150	.....	.6603	.7915	.....	....	.0003	.004
13,000	26,000	.6715	.7967	.0080	.100	....	....
13,500	27,000	.6728	.7959	.0087	.109	....	....
14,000	28,000	.7242	.8424	.0577	.721	....	....
150	.....	.7133	.8351	.....	....	.0486	.608
15,000	30,000	.7535	.8712	.0867	1.084	....	....
150	.....	.7417	.8632	.....	....	.0763	.960
17,000	34,000	.8474	.9618	.1790	2.238	....	....
150	.....	.8326	.9518	.....	....	.1666	2.083
19,000	38,000	.9720	1.0856	.3032	3.790	....	....
150	.....	.9562	1.0732	.....	....	.2391	3.613
21,000	42,000	1.1710	1.2811	.5004	6.255	....	....
150	.....	1.1524	1.2663	.....	....	.4337	6.043
22,000	44,000	1.3303	1.4381	.6586	8.233	....	....
150	.....	1.3102	1.4212	.....	....	.6401	8.001
22,500	45,000	1.4575	1.5441	.7752	9.690	....	....
23,000	46,000	1.5610	1.6670	.8884	11.105	....	....
23,500	47,000	1.7646	1.8693	1.0913	13.841	....	....
23,750	47,500	9.47		1.4700	18.375	....	....
21,800	43,600	9.54		1.5400	19.250	....	....

ELASTIC LIMIT.

Actual.

Lbs.	Kgs.	Lbs. per sq. in.	Kgs. per sq. cm.
13,500	6,140	27,000	1,898

BREAKING LOAD.

Original Sect.		Fractured Sect.	
Lbs. per sq. in.	Kgs. per sq. cm.	Lbs. per sq. in.	Kgs. per sq. cm.
47,500	3,340	69,840	4,910

Ultimate Elongation, per cent. of length = 19½.
Reduction of Area, per cent, = 31.99
Modulus of Elasticity = 24,365,000 lbs. on sq. in.
Modulus of Elasticity = 1,712,860 kilogrammes on sq. cm.

FINAL DIMENSIONS.

Length = 9″.54
Diameter = 0″.658

EXTENSION, RESTORATION, AND PERMANENT SET OF A SOLID CYLINDER OF STEEL, 3 INCHES LONG (BETWEEN SHOULDERS) AND 0.622 INCH DIAMETER, TAKEN FROM BREECH-RECEIVER FOR 11-INCH BREECH-LOADING RIFLE.

Weight per square inch of Section.	Extension per inch in Length.	Successive Extension per inch in Length.	Restoration per inch in Length.	Successive Restoration per inch in Length.	Permanent Set per inch in Length.	Successive Permanent Set per inch in Length.
Pounds.	*Inches.*	*Inches.*	*Inches.*	*Inches.*	*Inches.*	*Inches.*
1,000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000
2,000	.00000	.00000	.00000	.00000	.00000	.00000
3,000	.00000	.00000	.00000	.00000	.00000	.00000
4,000	.00033	.00033	.00033	.00033	.00000	.00000
5,000	.00033	.00000	.00033	.00000	.00000	.00000
6,000	.00033	.00000	.00033	.00000	.00000	.00000
7,000	.00033	.00000	.00033	.00000	.00000	.00000
8,000	.00033	.00000	.00033	.00000	.00000	.00000
9,000	.00033	.00000	.00033	.00000	.00000	.00000
10,000	.00033	.00000	.00033	.00000	.00000	.00000
11,000	.00033	.00000	.00033	.00000	.00000	.00000
12,000	.00033	.00000	.00033	.00000	.00000	.00000
13,000	.00033	.00000	.00033	.00000	.00000	.00000
14,000	.00033	.00000	.00033	.00000	.00000	.00000
15,000	.00033	.00000	.00033	.00000	.00000	.00000
16,000	.00067	.00034	.00067	.00034	.00000	.00000
17,000	.00067	.00000	.00067	.00000	.00000	.00000
18,000	.00067	.00000	.00067	.00000	.00000	.00000
19,000	.00133	.00066	.00100	.00033	.00033	.00033
20,000	.00233	.00100	.00100	.00000	.00133	.00100
21,000	.00300	.00067	.00100	.00000	.00200	.00067
22,000	.00400	.00100	.00100	.00000	.00300	.00100
23,000	.00467	.00067	.00100	.00000	.00365	.00067
24,000	.00533	.00066	.00100	.00000	.00433	.00066
25,000	.00633	.00100	.00133	.00033	.00500	.00067
26,000	.00700	.00067	.00133	.00000	.00567	.00067
27,000	.00767	.00067	.00133	.00000	.00633	.00066
28,000	.00900	.00133	.00100	—.00033	.00800	.00167
29,000	.00967	.00067	.00100	.00000	.00867	.00067
30,000	.01067	.00100	.00133	.00033	.00933	.00066
31,000	.01200	.00133	.00133	.00000	.01067	.00134
32,000	.01300	.00100	.00167	.00034	.01133	.00066
33,000	.01433	.00133	.00167	.00000	.01267	.00134
34,000	.01567	.00134	.00133	—.00034	.01433	.00166
35,000	.01700	.00133	.00133	.00000	.01567	.00134
36,010	.01800	.00100	.00133	.00000	.01667	.00100
37,000	.01967	.00167	.00133	.00000	.01833	.00166
38,000	.02133	.00166	.00167	.00034	.01967	.00134
39,000	.02433	.00300	.00167	.00000	.02267	.00300
40,000	.02567	.00134	.00167	.00000	.02400	.00133
41,000	.02733	.00166	.00167	.00000	.02567	.00167
42,000	.02867	.00134	.00167	.00000	.02700	.00133
43,000	.03033	.00166	.00200	.00033	.02833	.00133
44,000	.03300	.00267	.00233	.00033	.03067	.00234
45,000	.03433	.00133	.00200	—.00033	.03233	.00166
46,000	.03900	.00467	.00233	.00033	.03667	.00434
47,000	.04167	.00267	.02223	.00000	.03933	.00266
48,000	.04367	.00200	.00233	.00000	.04133	.00200
49,000	.04700	.00333	.00267	.00034	.04433	.00300
50,000	.05100	.00400	.00200	—.00067	.04900	.00467
51,000	.05533	.00433	.00300	.00100	.05233	.00333
52,000	.06067	.00534	.00233	—.00067	.05833	.00600
53,000	.06667	.00600	.00300	.00067	.06367	.00534
54,000	.06897	.00200	.00233	—.00067	.06633	.00266
55,000	.07867	.01000	.00300	.00067	.07567	.00934
56,000	.08333	.00466	.00300	.00000	.08033	.00466
57,000	.09500	.01167	.00300	.00000	.09200	.01167
58,000	.10233	.00733	.00333	.00033	.09900	.00700
59,000	.11800	.01567	.00333	.00000	.11467	.01567
60,000	.13700	.01900	.00367	.00034	.13333	.01866
61,000	.16900	.03200	0.00400	0.00033	0.16500	0.03167
62,000	0.30367	0.13467	(*)	(*)	(*)	(*)

* Specimen broke.

GENERAL SUMMARY.

Tensile Strength per sq. in.........lbs.	62,000	Original area of cross-section...sq. in.	0.3038
Elastic limit ....lbs.	19,000	Area after rupture.............sq. in.	0.1611
Extension per in. at elastic limit....in.	0.00133	Position of rupture.........⅛ from shoulder.	
Extension per in. at rupture.........in.	0.30367	Character of fracture...............Fibrous.	

times secure iron, if thin, capable of sustaining 60,000 pounds per square inch (4218 kilogs. per sq. cm.). A fair contract figure, and one that may be assumed in designing when the iron is to be thus selected and tested, would be considered to be 55,000 pounds (3867 kilogs.).

Steel boiler-plate of high tenacity is so certain to involve in its use risk of cracking, either in the process of construction, or later, after exposure to variations of temperature, and to alter so seriously and so uncertainly in all its physical properties, that specifications usually prescribe that it shall not exceed 60,000 pounds (4218 kilogs.) tenacity, and in some cases the figure is put even lower. When first introduced, tenacities much greater were allowed for steels, and great risks, and often serious accidents and losses of life and property, were the consequence. All good boiler-irons should be expected to stretch at least 20 per cent of the length of the test-piece, the latter being made at least four or five, and better eight or ten, diameters, or breadths in length. The best irons stretch 25 per cent, and the best steels even more. Thick plates have less tenacity and less ductility than thin.

The "bending test" is one which only the best of irons and the softer steels will bear. The strip cut from the sheet for test, the "coupon" as it is called, if of less than $\frac{3}{8}$ inch thickness, should bend completely over and be hammered flat upon itself, as in the figure.

FIG. 62.—BENDING TEST.

Steels subjected to the "temper test," by heating the sample red-hot and quenching in cold water, should then, if of good quality for boilers, be capable of successfully passing the bending test; but it is not usually demanded that it shall close down flat. If it bends to a circle of a diameter less than three times its own thickness, it is accepted. Steels subjected to the "drifting test" are commonly drilled with a $\frac{5}{8}$-inch drill, and the hole drifted out as large as possible. If it is enlarged to

double its original diameter, the metal is usually accepted, but it is sometimes demanded that it shall bear extension to two inches in diameter, as for example at Crewe, on the London and Northwestern Railway of Great Britain.

44. **Specifications of Quality,** as well as of kind and form, of materials proposed to be used in steam-boiler construction are so drawn as to secure not only an understanding on the part of the maker or vender of the exact nature of the intended provisions, but also a means of certainly determining whether those specifications and the contract are fully complied with.

Wrought-iron and steel, as has been seen, are very variable in strength and other qualities. For small iron parts, a tenacity of 55,000 to 60,000 pounds per square inch (3867 to 4218 kilogrammes per square centimetre) is usually called for; but the strength of plate or of large masses is rarely three fourths as great. The specification usually calls for "iron of the best quality," tough, of a definite tenacity, fibrous, free from cinder-streaks, flaws, lamination or cracks, uniform in quality, and with a prescribed elastic limit, and often a stated modulus of elasticity. Even the method of piling, heating, and rolling or hammering is specified.

As has been shown fully in the preceding chapters, the dimensions must be determined after a careful consideration of the character and the method of application of the load, as well as of its magnitude, and allowance must be made by the engineer for the effect of heat or cold, of repeated heating in the process of manufacture, for the rate of set under load, for the rapidity of its application, or for the effect of repeated or reversed strains.

The differences in the behavior of the several kinds of iron or steel under the given directions must be considered in proportioning parts. Thus unannealed iron or "low" steel will be chosen for parts exposed to steady and heavy loads; the use of annealed metal will be restricted to cases in which the primary requisite is softness or malleability; steel containing about 0.8 per cent carbon will be given the preference for parts exposed to moderate blows and shocks which are not expected to exceed the elastic resilience of the piece; tough, ductile metal,

preferably "ingot iron," will be chosen for parts exposed to shocks capable of producing great local or general distortion.

"Wöhler's Law" dictates the adoption of increased factors of safety, or of some equivalent device, as Launhardt's formula, when variable loads are carried. Thus the engineer is compelled to make a specification, in very important work, which shall prescribe all the qualities of materials and exactly the proportions of parts needed to make his work safe for an indefinite period.

Steel has such a wide range of quality that few difficulties are met with in its introduction into any department of construction. In boiler-work, however, it must be kept low in carbon, and therefore in tenacity; and in machinery and bridge work, also, its composition must be carefully determined upon, and as exactly specified.

The following are good specifications for boiler-work:

Steel Sheets.—Grain—To be uniform throughout, of a fine close texture. *Workmanship*—Sheets to be of uniform thickness, smooth finish, and sheared closely to size ordered. *Tensile Strength*—To be 60,000 pounds to square inch for firebox sheets, and 55,000 pounds for shell sheets. *Working Test*—A piece from each sheet to be heated to a dark cherry red, plunged into water at 60°, and bent double, cold, under the hammer; such piece to show no flaw after doubling.

Iron Sheets.—Grain—To be uniform throughout, showing a homogeneous metal with no layers or seams. *Workmanship*—Sheets to be of uniform thickness, smooth finish, and sheared closely to size ordered. *Tensile Strength*—To be 60,000 pounds to the square inch for firebox sheets, and 55,000 pounds for shell sheets. *Working Test*—A piece from each sheet to be bent cold to a right angle, showing no fracture. A piece bent double, hot, to show no flaking or fracture.

Specifications for Boiler Tubes.—Size—Locomotive tubes to be 12 feet long and 2 inches diameter; to be of iron, No. 11 gauge. *Quality of Metal*—When flattened under the hammer to show tough fibrous grain; when polished and etched with acid to show uniform metal and a close weld. *Working Tests*—When expanded and beaded into the flue-sheet to show

no flaws; to stand "swaging down" hot without flakes or seams.

The following are specifications for *Boiler* and *Firebox Steel:*

(1) A careful examination will be made of every sheet, and none will be received that show mechanical defects.

(2) A test strip from each sheet, tested lengthwise.

(3) Plate will not be passed for acceptance when of strength of less than 50,000 or greater than 65,000 pounds per square inch, nor if the elongation falls below twenty-five per cent.

(4) Should any sheets develop defects in working they will be rejected.

(5) Manufacturers must send one test strip for each sheet (this strip must accompany the sheet in every case), both sheet and strip being properly stamped with the marks designated by the company, and also lettered with white lead, to facilitate marking.

The U. S. Board of Supervising Inspectors of Steam-vessels restrict the stress on boiler stays and braces to 6000 pounds per square inch (4218 kilogrammes per square centimetre). For shells of boilers, a factor of safety of 6 is permitted in designing. The hydrostatic pressure applied in testing is one half greater than the steam-pressure allowed. All plates must be stamped by the maker with the tenacity, as determined by test, at the four corners and in the middle. The elongation is not noted, as the form of United States standard test-piece is unfitted to determine it. The contraction of area of section at fracture must be 0.15 when the tenacity is 45,000 pounds and one per cent *more* for each additional 1000 pounds.

Hot-short, or red-short, and cold-short irons are detected by the forge tests; the former is often found to be an excellent quality of iron if it can be worked into shape, as it is, when cold, tough and strong. Specially high qualities are rarely economical, as they usually cost too much to make the difference worth what is paid for it. Shapes difficult to make or roll are usually weaker than others. Mills will usually supply "pattern iron," charging a little extra for it; but it will often be found economical to order them, if such shapes are necessary. In designing,

however, it is well to avoid the introduction of peculiar shapes, if possible.

All wrought-iron, if cut into testing strips one and a half inches in width, should be capable of resisting without signs of fracture, bending cold by blows of a hammer, until the ends of the strip form a right angle with each other, the inner radius of the curve of bending being not more than twice the thickness of the piece tested. The hammering should be only on the extremities of the specimens, and never where the flexion is taking place. The bending should stop when the first crack appears.

All tension tests should be made on a standard test-piece of one and a half inches in width, and from one quarter to three quarters of an inch in thickness, planed down on both edges equally so as to reduce the width to one inch for a length of eight inches. Whenever practicable, the two flat sides of the piece should be left as they come from the rolls. In all other cases both sides of the test-piece are planed off. In making tests the stresses should be applied regularly, at the rate of about one ton per square inch in fifteen seconds of time.

All plates, angles, etc., which are to be bent in the manufacture should, in addition to the above requirements, be capable of bending sharply to a right angle at a working test, without showing any signs of fracture.

All rivet-iron should be tough and soft, and pieces of the full diameter of the rivet should be capable of bending until the sides are in close contact, without showing fracture.

All workmanship should be first-class; all abutting surfaces planed or turned, so as to insure even bearing, taking light cuts so as not to injure the end fibres of the piece, and protected by white lead and tallow. Pieces where abutting should be brought into close and forcible contact by the use of clamps or other approved means before being riveted together. Rivet-holes should be carefully spaced and punched, and in all cases reamed to fit, where they do not come truly and accurately opposite, without the aid of drift-pins. Rivets should completely fill the holes, and have full heads, and be countersunk when so required.

The following are specifications originally issued by the

United States Navy Department, which indicate the relation of variation of tenacity to the corresponding change in ductility where the quantity of carbon in steel is altered:

Tenacity.		Extension.
Lbs. per sq. in.	Kilos. per sq. cm.	Per cent.
60,000	4218	25
70,000	4921	23
80,000	5624	19
90,000	6327	12

A cold-bending test is demanded thus: Bend the strip over a mandrel of a diameter 1½ times the thickness of the plate, through an arc of 90°, and no cracks must appear with the softer grades, and any cracks seen in the case of the harder steels must be insignificant.

Every reputable maker stamps his iron, not only with the figures indicating the tenacity, as required by law, but also, in the case of thoroughly good qualities, with their names. Where the brand is not found, it is assumed by the experienced engineer that the metal is not of such high quality as to do credit to the maker. All good plate is expected to have fair tenacity and high ductility, and good flange-iron should not deteriorate appreciably in working.

45. **Choice of Quality of Metal for the Various Parts** of a boiler or other structure is made with the greatest care by the designer and by the constructor. The furnace, exposed as it is to variations of temperature, to the corrosive effect of hot gases, and to the mechanical wearing action of the cinder and coal carried by their rapidly moving currents, is made of the harder qualities of iron or steel already described. The tubes, flues, and the flue-sheets are composed of comparatively ductile material, such as may be safely shaped in accordance with the plans of the designer; the shell may be of cheaper material; while all stays and braces must be made of the strongest and toughest metal available. Each grade should be carefully prescribed, and the iron or steel proposed for use as carefully inspected and tested before it is introduced into the structure. It is sometimes advisable to substitute copper for iron, espe-

cially in the firebox; and in such cases sheet-copper of a tenacious and somewhat hard quality should be adopted. This material usually has about two thirds the strength of good iron, with greater ductility and flexibility, and resists the action of the furnace gases better than iron boiler-plate.

46. **The Methods of Working** the materials introduced into steam-boilers are adapted very carefully, in every case, to the known requirements of each quality so used. The frequent injury of steel and of hard iron plates by punching and by too abrupt change of form have led engineers to prescribe in many cases that all steel plate shall be drilled for the insertion of rivets, and not punched, and to direct the bending of the plate over rounded edges having comparatively large radii of curvature. All wrought-iron work in boilers, when subjected to any considerable change of form, should be worked at a bright-red heat, approaching the welding temperature; steel should be handled, in such cases, at a "cherry-red" heat.

Great alteration of shape, if effected at ordinary temperatures, should be made slowly and carefully, and it may even be well in some instances to allow intermissions in such operations sufficient to permit the particles some opportunity of self-adjustment. It may be taken as a general rule in the working of all materials for steam-boilers, that the methods and processes chosen should always be such as will be least likely to strain or to injure, either generally or locally, the iron or steel so used.

47. **Special Precautions in Using Steel** are found to be necessary to secure safe construction. Construction in steel demands more care than the making of iron boilers, and a good boiler-maker for the latter class of work is not necessarily a good worker of steel. In handling steel for boilers there should be no unnecessary local heating. If so heated, steel should always be subsequently annealed. The plates for the cylindrical shells of boilers should be carefully bent to shape when cold. The rivet-holes should usually be drilled, not punched, and the drilling should be done after the plates are bent to shape, and bolted together in position. The longitudinal joints in the shell are best made with double butt-strips, one

being placed inside, and the other outside, to form a "butt joint."

The tests of the plate supplied on specifications, and under contracts, should be even more carefully and minutely made than with iron; every operation must be more carefully conducted and supervised, and the completed boiler should be inspected and tested with the greatest possible care. If it is well made and of good material, it will be a more satisfactory construction than any iron boiler can possibly be; a mistake in accepting and using steel ill adapted to the purpose may produce an exceedingly dangerous and unsatisfactory boiler. Steel of good quality, and well adapted for other construction, is not necessarily safe for use in steam-boilers.

Many engineers would anneal every plate of steel used, whatever its apparent quality, to insure its safety in the structure, and it has even been suggested that it would be well, were it practicable, to anneal the whole boiler after completion.* Too great care cannot be taken in selecting the metal.

48. **Rivets and Rivet-Iron and Steel** are necessarily of especially good quality. The rivet must be strong, tough, and ductile, and capable of bearing the severest deformation at all temperatures without injury. It is customary to "head-up" rivets hot; but medium-sized and small rivets, in some localities, are worked cold, and this is the most trying test of quality possible. Rivets of less than $\frac{3}{8}$-inch (0.95 cm.) diameter are very commonly driven cold. Rivet-iron should, in the bar, have a tenacity approaching 60,000 pounds per square inch (4218 kgs. per sq. cm.), and should be as ductile as the very best boiler-plate when cold. The rivet should be capable of bearing the change of form incidental to its use without exhibiting a tendency to split; the head should not seriously harden or become brittle under the blows of the hammer; and the contraction on cooling, after it has been headed up, should not cause weakening by the stress incident to the strain so produced. A good iron rivet $\frac{5}{8}$ inch (1.6 cm.) diameter can be doubled up and hammered together, cold, without exhibiting

* Trans. Am. Soc. M. E., 1887, No. ccxlvi.

a trace of fracture. Such a rivet, split and "etched" on the cut surfaces, shows a smoothly curved grain, uniform texture and color, and no visible sign of the presence of slag. Such a rivet, made of good rivet-steel, will show absolute uniformity of surface, and no trace even of "grain."

The chemical composition of these rivet-steels should be as nearly as possible that of the best rivet-irons; they should contain the least possible proportion of the hardening elements, including carbon and manganese, as well as phosphorus, and should be so pure as to readily take a surface like that of a mirror, when polished.

49. **The Sizes of Rivets,** their form and strength, are quite well settled by experience and by test. The rivet consists, as supplied by the market, of a straight or slightly tapered body, circular in section, and having a head 1.5 or 1.6 the diameter of the shank; the latter is 2 to 3 or 4 per cent smaller than the hole which it is to fill, and tapers toward the end to a diameter about 0.95 that of the hole. The head is cylindrical, and has a thickness 0.7 or 0.75 the diameter of the body of the rivet. The length of the shank or body is 2.25 or 2.50 times the diameter of the hole, and the latter is often equal to the double thickness of plates held together by it. When in place, the small end is driven down by hand-hammers or by the riveting machines to form a cone-shaped or hemispherical head, the sheets riveted together being thus confined by the two heads and sustained by the strength of the shank against any force tending to separate them. The principal stresses exerted on the rivet are usually shearing. The rivets, when heated, should be brought up to a full, clear red heat. A simple rule sometimes used to determine the diameter of a rivets is that of Unwin, who makes this diameter

$$d = 1.2 \sqrt{t},$$

in which t is the thickness of the single plate or sheet. The following table is thus obtained, taking the nearest $\frac{1}{16}$th:

Thickness of Plate.	Diameter, d, of Rivet.	Thickness of Plate.	Diameter, d, of Rivet.
$\frac{1}{4}$	$\frac{1}{2} = 0.50$	$\frac{9}{16}$	$\frac{7}{8} = 0.86$
$\frac{5}{16}$	$\frac{9}{16} = 0.56$	$\frac{5}{8}$	$\frac{15}{16} = 0.94$
$\frac{3}{8}$	$\frac{11}{16} = 0.68$	$\frac{3}{4}$	$1\frac{1}{16} = 1.06$
$\frac{7}{16}$	$\frac{3}{4} = 0.75$	$\frac{7}{8}$	$1\frac{1}{8} = 1.13$
$\frac{1}{2}$	$\frac{13}{16} = 0.80$	1	$1\frac{1}{4} = 1.25$

The driven rivet is something like four or five per cent larger than the undriven.

The following table gives the proportions of rivets adopted in some of the best establishments in the United States,* and the relative strength of joint secured:

TABLE OF THE PROPORTIONS OF RIVETS.

Thickness of plate	$\frac{1}{4}''$	$\frac{5}{16}''$	$\frac{3}{8}''$	$\frac{7}{16}''$	$\frac{1}{2}''$
Diameter of rivet	$\frac{5}{8}$	$\frac{11}{16}$	$\frac{3}{4}$	$\frac{13}{16}$	$\frac{7}{8}$
Diameter of rivet-hole	$\frac{11}{16}$	$\frac{3}{4}$	$\frac{13}{16}$	$\frac{7}{8}$	$\frac{15}{16}$
Pitch—single-riveting	2	$2\frac{1}{16}$	$2\frac{1}{8}$	$2\frac{3}{16}$	$2\frac{1}{4}$
Pitch—double-riveting	3	$3\frac{1}{8}$	$3\frac{1}{4}$	$3\frac{3}{8}$	$3\frac{1}{2}$
Strength of single-riveted joint	.66	.64	.62	.60	.58
Strength of double-riveted joint	.77	.76	.75	.74	.73

Plates more than $\frac{1}{2}''$ thick should never be joined with lap-joints. When it is necessary to use them a butt-joint with a double fish-plate should always be used. In recommending the above proportions we assume that the workmanship is always fair.

The common proportions of rivets, as given by Unwin,† are seen in the accompanying figure; that illustrated is of such form as will permit the formation of the conical head, the total length being about $2\frac{1}{4}$ times the diameter when a double thickness of plates is to be secured together.

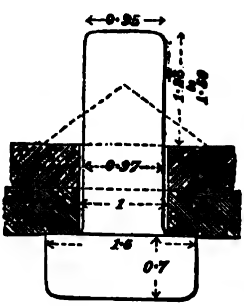

FIG. 63.

The next figures exhibit the difference in proportions of rivets for hand-riveting and for steam-riveting, as given by the same authority; the first figure showing two forms of head for hand-work, the second two for

* *Locomotive*, July, 1882.

† Machine Design.

steam-riveted work: one of each pair is set in a straight hole,

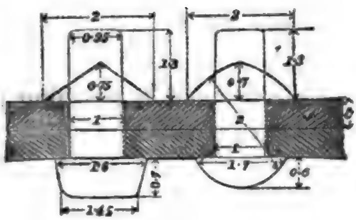

FIG. 64.

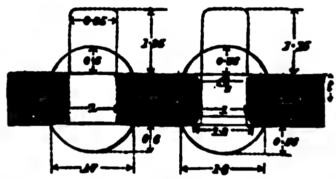

FIG. 65.

the other in a chamfered hole. The next figure gives the proportions for a countersunk rivet, used in ship-building.

50. The Strength of Seams, when riveting is used, varies with the character of the metal, the method of riveting, and the quality of workmanship. A single-riveted joint has usually not far from 60 per cent of the strength of the solid sheet, a double-riveted seam 70 per cent; and the strength may be still further increased by adding to the number of rows of rivets, with proper distribution. The joint is so proportioned that the fracture will occur by shearing the rivets rather than by breaking out the edge of the sheet or tearing away the lap bodily. The lap usually extends beyond the rivet-hole about 1.5 times the diameter of the rivet.

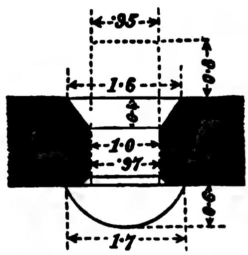

FIG. 66.

To secure maximum "efficiency" of seam, i.e., equal and maximum resistance in all directions of possible stress, it is evident that the joint must be equally liable to tear along the line of rivets, to shear the rivets, and to tear them out by pulling them through the lap. For a single-riveted joint therefore, if F represent the tearing force, T the tenacity of the sheet, SS' the shearing resistance of the rivet and sheet, C its resistance to crushing, p the "pitch," and d the diameter of the

rivets, l the width of lap, and t the thickness of the sheet, we must have

$$F = \tfrac{1}{4}\pi d^2 S' = Cdt = (p - d)Tt;$$

or, if the lap is made over strong, as above, and if crushing is not anticipated, both of which are usual conditions,

$$F = \tfrac{1}{4}\pi d^2 S = (p - d)Tt,$$

and

$$p = \frac{\frac{1}{4}\pi d^2 S + dtT}{Tt} = \frac{1}{4}\frac{\pi d^2 S}{tT} + d.$$

Where, as sometimes is the case, the joint is a butt-joint and the rivets are thus "in double shear,"

$$p = \frac{\frac{1}{2}\pi d^2 S}{Tt} + d;$$

and the same expression serves for the case of double-riveted seams made, as with single-riveting, with a lap, but having a second line of rivets behind and reinforcing the first.

Where the rivet and the plate are of the same material, or wherever the resistance to shearing and the tenacity may be taken as substantially equal, the formula

$$p = d + \frac{0.7854 n d^2}{t}$$

may be adopted, in which p, d, n, and t are, respectively, the pitch of rivets, centre to centre, the diameter of rivet, the number of parallel rows, and the thickness of sheet.

The following tables represent proportions for adoption in designing, the ratio of T to C being taken for iron and steel of various qualities, as assumed by Unwin:*

* See Machine Design, by W. C. Unwin. London: Longmans, Green & Co.

SINGLE-RIVETING.

t	d in Inches. Nominal.	d in Inches. Actual.	Iron Rivets and Plates. Punched Plates.		Iron Rivets and Plates. Plates Drilled.		Steel Rivets and Plates. Plates Punched.		Steel Rivets and Plates. Plates Drilled or Punched and Annealed.	
			Pitch p for values of $\frac{T}{C}$ = 0.75	0.85	0.95	1.0	1.05	1.15	1.25	1.35
$\frac{5}{16}$	$\frac{11}{16}$	0.72	2.45	2.25	2.1	2.0	2.0	1.85	1.8	1.7
$\frac{3}{8}$	$\frac{3}{4}$	0.78	2.5	2.3	2.1	2.1	2.0	1.9	1.8	1.7
$\frac{7}{16}$	$\frac{13}{16}$	0.85	2.6	2.4	2.2	2.15	2.1	2.0	1.9	1.8
$\frac{1}{2}$	$\frac{7}{8}$	0.92	2.7	2.5	2.3	2.2	2.1	2.1	2.0	1.9
$\frac{5}{8}$	$\frac{15}{16}$	0.98	2.6	2.4	2.3	2.2	2.1	2.0	2.0	1.9
$\frac{3}{4}$	$1\frac{1}{16}$	1.10	2.8	2.6	2.4	2.4	2.3	2.2	2.1	2.0
$\frac{7}{8}$	$1\frac{1}{8}$	1.17	2.9	2.7	2.5	2.5	2.4	2.25	2.2	2.15
1	$1\frac{1}{4}$	1.30	3.1	2.9	2.7	2.6	2.6	2.45	2.4	2.3

DOUBLE-RIVETING.

t	d in Inches. Nominal.	d in Inches. Actual.	Iron Rivets.—Plates Punched.	Iron Rivets.—Plates Drilled.		Steel Rivets.—Plates Punched.	Steel Rivets.—Plates Drilled.
			Pitch of rivets for value of $\frac{T}{C}$ = 0.85	1.00	1.10	1.20	1.35
$\frac{5}{16}$	$\frac{11}{16}$	0.72	3.8	3.3	3.1	2.9	2.7
$\frac{3}{8}$	$\frac{3}{4}$	0.78	3.8	3.4	3.1	2.9	2.7
$\frac{7}{16}$	$\frac{13}{16}$	0.85	3.9	3.5	3.2	3.0	2.8
$\frac{1}{2}$	$\frac{7}{8}$	0.92	4.0	3.6	3.4	3.2	2.9
$\frac{5}{8}$	$\frac{15}{16}$	0.98	3.9	3.4	3.2	3.0	2.8
$\frac{3}{4}$	$1\frac{1}{16}$	1.10	4.0	3.6	3.4	3.2	3.0
$\frac{7}{8}$	$1\frac{1}{8}$	1.17	4.1	3.7	3.5	3.3	3.1
1	$1\frac{1}{4}$	1.30	4.4	3.9	3.7	3.5	3.3

Joints proportioned as above range, in their "efficiencies," from 40 to 60 per cent in the single-riveted seams, and from 60 to 80 per cent for double-riveting; the smallest rivets and thinnest plates giving the smallest, and the larger work the largest, values. The average efficiencies may be taken as follows:

Single-riveting:								
Plate-thickness	$\frac{5}{16}$	$\frac{3}{8}$	$\frac{7}{16}$	$\frac{1}{2}$	$\frac{5}{8}$	$\frac{3}{4}$	$\frac{7}{8}$	1
Efficiency	55	55	53	52	48	47	45	43
Double-riveting:								
Efficiency	75	73	72	71	67	66	64	63

The strength of a seam is obtained by multiplying the resistance of the solid sheet by the efficiency of the joint.

The strength of well-made joints, as exhibited by test, in proportion to strength of the original plate, according to Clarke, are for plates $\frac{3}{8}$-inch thick and less, for the best English Yorkshire iron:

		Working Strength.
Original strength of plate.......	100	11,000 lbs. per sq. inch.
Single-riveted lap-joint..........	60	6,700 " "
Double-riveted lap-joint.........	72	8,000 " "
Double-riveted butt-joint.........	80	9,000 " "

Fairbairn found the strength of joints to be as follows:

Strength of plate..........	100	Bursting tension.	34,000 lbs.
Double-riveted joint.......	70	Proof tension....	17,000 "
Single-riveted joint.......	56	Working tension.	4,250 "

the working tension being taken as $\frac{1}{8}$ of the bursting tension. For cast-iron pipes the working tension may be estimated at $\frac{1}{6}$ the bursting pressure, and at about

16,500 lbs. per sq. inch for bursting tension,
5,500 " " " " proof tension,
2,750 " " " " working tension.

Welded joints for boilers have, if perfect, the same strength as the original plate, but they are apt to be uncertain.

The thickness of plates is limited for best work. Very thin plates cannot be well calked, and thick plates cannot be safely riveted. The limits are about $\frac{1}{4}$ of an inch for the lower limit, and $\frac{3}{4}$ of an inch for the higher limit. The riveting machine only can be used for very thick plates, a thickness of half an inch being about the limit of hand-riveting.

In some cases the seams of the shells or the flues of boilers are put together in *helical* form, and some increase of strength is thus secured in the longitudinal at the expense of the girth-seams. If n represent the ratio of the projected length of the seam on the circumference to the corresponding length of the

projection longitudinally, the ratio of strength, as compared with the common seam, is measured by the ratio

$$m = \frac{2n^2 + 2}{n^2 + 2}.$$

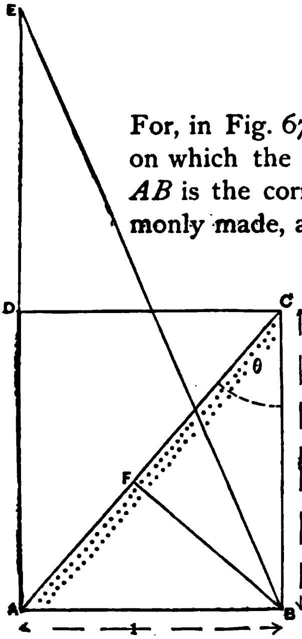

FIG. 67.

For, in Fig. 67, let ABC represent a part of a sheet on which the diagonal AC is the line of the joint; AB is the corresponding longitudinal joint, as commonly made, and BC the girth seam.

Then the stress per unit of length of AB will be unity; that on BC will be 2, and the total stresses will be, respectively, 2 and n, where n measures the ratio of BC to AB, or the "rake" of the seam. The total resultant stress will be AC on the joint BE, and its normal component will be BF, the sum of the components of those on the longitudinal and girth seams, AB and BC, resolved perpendicular to AC, and the intensity of that stress is the quotient of this sum divided by the length, AC, of the seam. Hence the intensity on AB will be

$$t_1 = \frac{2 \times AB}{AB} = 2;$$

that on BC will be

$$t_2 = \frac{1 \times nAB}{nAB} = 1;$$

that on AC will be

$$t_3 = \frac{2 \sin \theta + n \cos \theta}{\sqrt{1 + n^2}}.$$

But

$$\sin\theta = \frac{1}{\sqrt{1+n^2}}; \quad \cos\theta = \frac{n}{\sqrt{1+n^2}};$$

and

$$t_2 = \frac{n^2+2}{1+n^2} \quad \text{and} \quad \frac{t_1}{t_2} = \frac{n^2+2}{2n^2+2} = \frac{1}{m}.$$

When n is given the values below, the ratios of strength of seam are as tabulated.

STRENGTH OF HELICAL SEAM.

(Common longitudinal seam = 1.)

n	m	n	m
0	1.0	1.75	1.6
$\frac{1}{2}$	1.3	2.00	1.7
1	1.4	3.00	1.8
1.25	1.5	∞	2.0
1.5			

When $n = 0$ the joint is parallel with the axis of the cylinder; it becomes a longitudinal seam. When $n = \infty$, it becomes a girth-seam of twice the relative strength. When the angle of "rake" is 30°, the gain is 10 per cent; when 45°, the gain becomes 0.4. It is obvious that this form of seam is very wasteful of metal, if so much inclined as to secure any considerable gain of strength, if the boiler or the flue is built of a succession of ring courses laid side by side; in such constructions as Root's "spiral pipe," in which the courses are helical, this objection does not hold.

The "factor of safety," as stated where reference is made to the strength of steam-boilers, is usually misleading, as, for example, in the U. S. regulations. Pressures one sixth those computed from the reports of tests of strength of the plate are permitted; but the real factor of safety is obtained by multiplying this nominal factor by the coefficient of strength of seam. Thus, where the law allows six the real factor is $0.56 \times 6 = 3.36$

for the single-riveted seam, or $0.7 \times 6 = 4.2$ for double-riveting, Fairbairn's coefficients being accepted. The *real* factor should not be less than six, and some authorities, following Rankine, would make it eight, and others even ten.

51. **Punched and Drilled Plates** usually differ in strength, but each may be either stronger or weaker than unperforated metal of equal area of fractured section. When the metal is very soft and ductile, the operation of punching does no appreciable injury, and the Author has sometimes found it actually productive of increased strength, the flow of particles from the hole into the surrounding parts causing stiffening and strengthening. With most steel and with hard iron the effect of punching is often to produce serious weakening and a tendency to crack, which has in some cases resulted seriously. With metal of the first class, punching is perfectly allowable; with iron or steel of the second class, drilling should always be practised. It is customary, in the practice of the most reputable engineers and builders, to drill all steel plates, but usually to punch iron. Sometimes the steel plate is punched with a punch of smaller diameter than the proposed rivet, and is subsequently reamed out or counterbored to size. It is generally assumed that this method is perfectly safe.

Messrs. Greig and Eyth, after a long and carefully conducted investigation, say:*

"The experiments show that the plates invariably lose part of their tensile strength in the section of solid material left between the rivets of a seam, this loss being greatest in lap-joints. It is also greater in punched than in drilled plates (iron as well as steel), and greater in plates riveted together by steam, than in those riveted by hydraulic pressure. On the other hand, the strength of rivets against shearing is greater than its normal figure, especially in lap-joints.

"The usefulness of double-riveting appears to be mainly due to the fact that it more effectually prevents lap-jointed plates from bending under stress. At the same time the zig-zag riveting generally adopted, in double-riveting, increases

* Lond. *Engineering*, June 29, 1879.

the tensile resistance of the material between the rivets considerably beyond its normal figure.

"Butt-joints, with a cover on one side of the plate only, gave no advantage at all, the cover behaving simply as an intermediate plate attached to the two main pieces by an ordinary lap-joint. A marked improvement could, no doubt, be obtained by giving the cover greater thickness, so as to prevent its bending.

"The most effective seams, as to tensile strength, were butt-joints with two covers, as not only do they nearly double the shearing strength of each rivet, but they entirely prevent the bending of the main plates. The main fact resulting from the tests of parts of boilers and complete boilers under hydraulic pressure was the impossibility of bursting an ordinary rivet-seam in this way, the compression of the rivet and the elongation of the rivet-hole resulting invariably in leakage, which prevented the necessary pressure from being obtained. Each rivet becomes its own safety-valve, and the strain put on the weakest part of the structure never reached more than 70 per cent of the breaking strain. This is the point where additional hardness of the material would be most useful, as it would prevent the opening of the rivet-holes, which now makes a boiler useless long before the breaking strain is reached." *

Good steel is much more enduring than any iron, both against ordinary wear and extraordinary strain.

The results of experiments on the best British steel for ship-building and for boilers, as reported to Lloyds, show that the injury done by punching is less as the plates are thinner, amounting, in the cases reported, to less than 10 per cent in sheets ¼ inch (0.6 cm.) thick, and rapidly increasing, becoming 20 per cent at ⅜ inch (1 cm.), and is still more serious with the heavy plate used for large ships and for boilers. But the injury was discovered to be local, and confined to a shell lining the punched hole, and but about one eighth of an inch (0.3 cm.) in thickness. This can be readily cut out, and the punched and counterbored, or reamed, holes produce no observable weak-

* Lond. *Engineering*, 1879.

ness. In many instances no special precautions are taken in this direction where the metal is less than one half inch (1.25 cm.) in thickness.

52. **Hand-riveting and Steam-riveting** are both practised by good makers, and authorities are somewhat divided in opinion as to their relative merit. With either system, good work may be done by a good workman; by either method, dangerously defective boilers may be produced. With a properly designed riveting machine of the right size for its work, and carefully manipulated, very perfect work may be done. Careless handling produces distorted rivets, eccentrically placed heads, and sometimes causes the formation of a "fin" on the rivet, which, entering between the sheets to be riveted together, holds them apart and causes leakage along the seam. When the plates are well adjusted, in metallic contact, and perfectly secured, before the rivet is "headed up," this last defect is not likely to appear. The careful adjustment of the rivet-head to the die which supports it against the blow of the machine, and the exact alignment of rivet and striking die, will prevent distortion of the rivet by the blow. Sometimes the machine is too light for its work; in such cases two blows may be necessary to completely form the head and to expand the body of the rivet sufficiently to fill the rivet-hole.

In hand-riveting the action of the hammer often hardens the metal in the head, and gives it such rigidity and brittleness that it may even fly off at the last stroke of the riveting hammer. The cone-shaped head is a comparatively weak form, and it is better to use a cup-shaped die, or former, and a larger hammer striking fewer and heavier blows, to form a hemispherical head, which latter is much stronger, and neater in appearance. Work of this kind may be quite as good as the best machine-riveting, but it is usually—not invariably—more costly.

Riveting machines constructed with two dies moved independently—the one a hollow die, having for its office the closing up of the lap simply; the other a solid die, which immediately follows up the first and sets up the rivet—are probably much better than the more common form of riveter having one die

only. Messrs. Greig and Eyth found the following to be the pressures attained on the heads of ⅝-inch steel rivets:*

	Lbs.
Steam-riveter	82,380
Hydraulic stationary	86,360
Hydraulic portable	44,018
Power light blow	69,384
Power heavy blow	115,640

The best work was done by the steam-riveter.

They conclude that—

"The well-known fact of the superiority of riveting by machinery over hand-riveting has been again demonstrated most conclusively, while the experiments have shown that the effects of steam-riveting is, to say the least of it, not inferior to hydraulic riveting as far as the quality of the rivet is concerned, but that the hydraulic riveting is distinctly superior as to its effects on the plate, which is less injured by the slow pressure of the hydraulic ram.

"Steel showed in this respect a decided superiority over iron beyond the proportion due to its greater tensile and shearing strength."

The conclusions of Mr. J. M. Allen are that machine-riveting probably results in a greater proportion of defective rivets than any other one cause. Machine-riveting to make good work must be very carefully done. The rivet-hole must be truly in line with the machine dies. The holes in the two plates must also be in line with each other. If there is an offset between them, the rivet is sure to be a very bad one. The most satisfactory riveting of boiler-plates is done by a properly constructed and used button-set. By this means better and more rapid work can be done than by hand-riveting. A well-constructed machine will work quicker than the set, but we have rarely seen a complete job of machine-riveting which left nothing to be desired. It was not the fault of the machine, however. In hand-riveting the excellence of the joint depends

* Lond. *Engineering*, June 29, 1879.

upon the form of the set. With an improper set it is impossible to do good work, no matter how skilful the workmen may be.

53. **Welded Seams** are considered better than riveted, where facilities for welding are provided such that the weld may be made with certainty and invariably perfect. Unless special and very complete arrangements are made for securing absolute metallic contact, a good welding heat without oxidation, and thorough union by pressure or impact, welds are very apt to prove exceedingly unreliable. A gas-furnace, with a de-oxidizing flame of large volume and covering a considerable length of seam, has done good work, and some makers are adopting this system to the exclusion of riveting. Large boilers are sometimes made without the use of a single rivet in any important line of junction. It seems possible, and even probable, that welding may in time displace riveting in all good boiler construction.

54. **"Struck-up" or Pressed Shapes** are adopted, in preference to riveted or even welded parts, wherever the form and size of the piece will admit. Dome-tops, manhole and hand-hole plates, and sometimes large tube or flue sheets, are thus made. The piece is made by compressing the sheet of which it is to be constructed between a pair of dies, and thus compelling it to take the shape of the intermediate space, which is that of the finished piece. The pressure is commonly applied by means of the hydraulic press. Small pieces are shaped in the drop-press, or drop-hammer, in which the dies are forced together by the blow of a heavy "tup," or hammer, falling from a height of from two to six feet or more, according to the size and the intricacy of form of the part to be produced.

55. **Cast and Malleableized Iron, Brass, and Copper** all have limited application in steam-boilers.

Cast-iron is used in the construction of manhole plates, of some of the fittings, and even, in many instances, in the heads of plain cylindrical and flue boilers. Its use is, however, always to be deprecated where wrought-iron can be substituted. When it is adopted, in places in which it may be subjected to heavy loading, and where its failure may prove a serious matter,

great care should be taken to secure the best possible quality. It would be advisable, probably, in such cases, to use "gun-iron," as it is called, which is cast-iron of the best grades, melted in an "air-furnace"—a reverberatory furnace—and refined by "poling," or stirring with a pole, usually a birch sapling, until its quality and composition are satisfactory. No contact being allowed with the fuel or any flux or other source of contamination by phosphorus or other objectionable element, greater strength and toughness can be obtained than when the melting is done in a "cupola" furnace, in which the iron, fuel, and any flux that may be used are mixed together. The process is expensive; but the product is correspondingly valuable, the tenacity of good gun-iron exceeding, often, 30,000 pounds per square inch (2109 kgs. per sq. cm.), and its elasticity and elastic resilience approximating similar properties in wrought-iron.

Malleableized cast-iron is usually given application in small castings forming parts of the various attachments to boilers. It is made by selecting a free-flowing cast-iron, as light in grade as possible, making the castings in the usual way and then subjecting them to a process of prolonged annealing at a red heat in the presence of substances capable of abstracting the carbon, such as iron-ore, blacksmith's scale, or other materials rich in oxygen. The abstraction of the carbon thus leaves the casting stronger, somewhat ductile and malleable, and, as a rule, a much safer material than when in its original state; it has become a crude wrought-iron. Only small pieces can be successfully made in this manner, except by annealing for days, or even several weeks; the larger the casting the longer the time demanded. Some so-called "steel-castings" are thus made.

Brass and bronze are used mainly in the encasing of pressure-gauges, water-gauges, and similar appurtenances, in the construction of gauge and other cocks, and in valves and their seats; it is less liable to be cut away by steam, or by water, and hence brass valves keep tight longer than do iron valves or cocks. Bronze is better than brass, but its higher cost precludes its general use. Muntz metal, which consists of copper 60, zinc 40, and gun-bronze, 90 copper and 10 tin, are the most generally useful compositions; but the brasses in common use generally

contain more or less of lead, and the bronzes are often also similarly adulterated. For surfaces exposed to friction the addition of lead is thought by many to be an advantage. The strongest of all such alloys is that consisting of copper 43, zinc 55, and tin 2, or one having a somewhat less proportion of tin; this has been called by the Author, its discoverer,* "maximum bronze." The presence of zinc or other foreign element in the real bronzes is found to be particularly objectionable in those alloys intended for use in salt water, as it renders the latter especially liable to injury by local and rapid corrosion.

56. **The Strength of the Shells and Flues** of boilers may be readily calculated when the data can be safely relied upon. The two forms are subject to quite different laws, however; and even the strength of cylinders subjected to internal pressure, as are the cylindrical shells of steam-boilers, when thick, is calculated by different methods from those applicable when of thin plate; but it is not asserted that the heavy shells of large marine boilers, in which the metal is from three quarters to, sometimes, above an inch thick, may not be properly calculated by the rule applying to thick cylinders of cast-iron or other non-ductile material.

Cylindrical Boiler-Shells, and other thin cylinders, have a thickness which is determined by the tenacity of the metal and the character of the riveted or other seam. If p be the internal pressure, T the mean tenacity to be calculated upon along the weakest seam, r the semidiameter, and t the thickness, we have for axial stresses for equilibrium,

$$p\pi r^2 = 2\pi r t T,$$

and

$$p = \frac{2tT}{r}; \quad t = \frac{pr}{2T}. \quad . \quad . \quad . \quad . \quad . \quad . \quad (1)$$

But for transverse stresses tending to rupture longitudinal seams,

$$pr = tT,$$

* See "Materials of Engineering:" The Alloys.

and

$$p = \frac{tT}{r}; \quad t = \frac{pr}{T}. \quad \ldots \ldots \quad (2)$$

With seams of equal strength in both directions, therefore, the cylinder is at the point of rupture along the longitudinal seams, while capable of bearing twice the pressure on girth seams. It is evident that spheres have twice the strength of cylinders of equal diameter.

Thick cylinders are considered later, as they are usually made in cast-iron.

Flat Boiler-heads are made both in wrought and cast iron. For these Clark's rules may be used.*

For elastic deflection,

$$d = \frac{d_1}{44}. \quad \ldots \ldots \quad (3)$$

For maximum pressure,

$$p = 0.215\frac{tT}{d_1}, \quad \ldots \ldots \quad (4)$$

or, for iron,

$$p = 10{,}000\frac{t}{d_1}. \quad \ldots \ldots \quad (5)$$

For steel,

$$p = 11{,}500\frac{t}{d_1}. \quad \ldots \ldots \quad (6)$$

For cast-iron,

$$p = 4{,}000\frac{t}{d_1}, \quad \ldots \ldots \quad (7)$$

when t is the thickness, d_1 the diameter, both in inches, p the pressure and T the tenacity, both in pounds per square inch.

* Inst. C. E., vol. liii., Abstracts. London, 1877–78.

For spherical ends,

$$p = \frac{at}{\frac{d_1^2}{4v} + v}, \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (8)$$

where a is 108,000 for wrought-iron, 125,000 for steel, 45,000 for cast-iron, and v is the versed sine or rise of the head.

Lloyd's Rule for cylindrical shells of boilers is

$$p = \frac{abt}{d}, \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (9)$$

in which a is a constant, 155 to 200 for iron and 200 to 260 for steel, b the percentage of strength of solid sheet retained at the joint, t is the thickness of the plate, and d the diameter of the shell. The value of b is thus reckoned (n = number of rows of rivets):

$$b = 100\frac{p_1 - d_1}{p_1}, \text{ for the plate;}$$

$$b = 100\frac{na_1}{p_1 t}, \text{ for rivets in punched holes;}$$

$$b = 90\frac{na_1}{p_1 t}, \text{ for rivets in drilled holes.}$$

The least of these values is taken. Here p_1 is the pitch of rivets, d_1 is their diameter, a_1 is the area of the rivet-section. When in double-shear, $1.75a_1$ is taken for a_1. The factor of safety is taken at 6, and boilers are tested by water-pressure up to $2p$.

The iron is expected to have a tenacity of at least 21 tons per square inch; steel must bear 26 tons (3307 to 4095 kilogs. per sq. cm.).

Welds are found, when well made, to carry 75 to 85 per cent of the strength of the sheet.

Steam-pipe is usually made with an enormous excess of

strength to meet accidental stresses, such as those due to motion of water within them. The Author has tested pipes broken by "water-hammer," as the engineer calls it, to 1000 pounds per square inch (70 kilogrammes per sq. cm.) *after* it had been thus cracked in regular work in a long line, while the steam-pressure was less than 100 pounds (7 kilogs. per sq. cm.). They had all been previously tested to about one third this pressure.

Cylinders of cast-iron, for steam-generators or for steam-engines, are usually given a thickness greatly in excess of that demanded to safely resist the steam-pressure; often, according to Haswell,

$$t = \frac{dp}{2500} + \frac{1}{8}, \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (10)$$

for vertical cylinders, where d is the internal diameter, and

$$t = \frac{dp}{2000} + \frac{1}{8}, \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (11)$$

for horizontal cylinders of considerable size.

In metric measures, kilogrammes and centimetres, these formulas become

$$t = \frac{dp}{200} + \frac{1}{3}, \text{ nearly}; \quad . \quad . \quad . \quad . \quad . \quad (12)$$

$$t = \frac{dp}{160} + \frac{1}{3}, \text{ nearly}. \quad . \quad . \quad . \quad . \quad . \quad (13)$$

If r_1 is the external and r_2 the internal radius, T the tenacity of the metal, t its thickness, and p the intensity of the internal pressure, we have, for the *thin cylinder*, as an equation for equilibrium,

$$pr_2 = T(r_1 - r_2) = Tt, \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (14)$$

and,

$$r_2 = \frac{Tt}{p}; \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (15)$$

$$t = r_1 - r_2 = \frac{pr_2}{T}; \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (16)$$

$$p = \frac{Tt}{r_2}. \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (17)$$

For the *thick cylinder*, however, the resistance at any internal annulus of the cylinder is less than T.

Thick Cylinders, technically so called, are those which are of such thickness that the mean resistance falls considerably below the full tenacity of the metal, as exhibited in thin cylinders, in low-pressure steam-boiler shells, for example. Such cylinders are seen in the "hydraulic" press, and in ordnance.

*Barlow** assumes the area of section unchanged by stress, although the annulus is thinned somewhat by linear extension. If this is the fact, as the tension on any elementary ring must vary as the extension of the ring within the elastic limit, the stress in such element will be proportional to the reciprocal of the square of its radius, i.e., it will be

$$p \propto \frac{1}{r^2}; \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (18)$$

and, taking the total resistance as $p'r_1$, when p' is the internal fluid pressure, since the maximum stress at the inner radius is T, that on the inner elementary annulus is Tdx, and on any other annulus $\frac{Tr_2^2}{x^2}dx$; while the total resistance will be, on either side the cylinder,

$$p_1 r_2 = Tr_2^2 \int_{r_2}^{r_1} \frac{dx}{x^2} = T\frac{r_2(r_1 - r_2)}{r_2 + (r_1 - r_2)} = T\frac{r_2 t}{r_2 + t}. \qquad (19)$$

* Strength of Materials, 1867, p. 118.

The maximum stress is at the interior, and may be equal, as taken above, to the tenacity, T, of the metal; then

$$T = \frac{p_1 r_1}{t} = \frac{p_1(r_2 + t)}{t}, \quad . \quad . \quad . \quad . \quad . \quad (20)$$

and the thickness

$$t = \frac{p_1 r_2}{T - p_1}, \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (21)$$

while the ratio of the radii

$$\frac{r_1}{r_2} = \frac{Tt}{p_1} \div \frac{t(T - p_1)}{p_1} = \frac{T}{T - p_1}. \quad . \quad . \quad . \quad (22)$$

Lamé's Formula, which is more generally accepted, and which is adopted by Rankine, gives smaller and more exact values than that of Barlow. In the above, no allowance is made for the compressive action of the internal expanding force upon the metal of the ring. The effect of the latter action is to make the intensity of pressure at any ring less than before by a constant quantity,

$$p \propto \frac{a}{r^2} - b,$$

and the tension by which the ring resists that pressure greater,

$$p^1 \propto \frac{a}{r^2} + b.$$

When $r = r_1, p = 0$; when $r = r_2, p = p_1$;

$$\text{then } p_1 = \frac{a}{r_2^2} - b, \quad \text{and} \quad 0 = \frac{a}{r_1^2} - b;$$

$$a = p_1 \frac{r_1^2 r_2^2}{r_1^2 - r_2^2}; \quad b = p_1 \frac{r_2^2}{r_1^2 - r_2^2};$$

and the maximum possible stress on the inner ring is

$$T = \frac{a}{r_2^2} + b$$
$$= p_1\left(\frac{r_1^2}{r_1^2 - r_2^2} + \frac{r_2^2}{r_1^2 - r_2^2}\right).$$

$$T = p_1\frac{r_1^2 + r_2^2}{r_1^2 - r_2^2}; \quad \dots \dots \dots \quad (23)$$

$$p_1 = T\frac{r_1^2 - r_2^2}{r_1^2 + r_2^2}; \quad \dots \dots \dots \quad (24)$$

and the ratio of inner and outer radii is

$$\frac{r_1}{r_2} = \sqrt{\frac{T + p_1}{T - p_1}}. \quad \dots \dots \quad (25)$$

Of these two formulas, the first gives the larger and consequently safer results, and, in the absence of certain knowledge of the distribution of pressure within the walls of the cylinder, is perhaps best.

For thick spheres, Lamé's formula becomes

$$p_1 = T\frac{2(r_1^3 - r_2^3)}{r_1^3 - 2r_2^3}. \quad \dots \dots \quad (26)$$

$$\frac{r_1}{r_2} = \sqrt[3]{\frac{2(T + p_1)}{2T - p_1}}. \quad \dots \dots \quad (27)$$

Clark's formula* is more recent than the preceding. It is assumed that the expansion of concentric rings into which the cylinder may be conceived to be divided is inversely as their radii, and that the curve of stress will become parabolic if so laid down that the radii shall be taken as abscissas and the stresses as ordinates, the total resistance thus varying as the

* Rules and Tables, p. 687.

logarithm of the ratio of the radii. Then if the elastic limit be coincident with the ultimate strength, and

$T =$ the tenacity of the metal,
$R =$ the ratio, external diameter divided by internal,
$p =$ the bursting pressure,

$$p = T \times \text{hyp} \log R; \quad \ldots \ldots \quad (28)$$

$$R = e^{\frac{p}{T}}. \quad \ldots \ldots \ldots \ldots \quad (29)$$

In other cases, instead of T take the value of the resistance at the elastic limit, and base the calculation of proportions upon the elastic limit and its appropriate factor of safety. The formulas as given are considered applicable to cast-iron.

The strength of thick cast cylinders *with heads cast in* may, however, sometimes be far in excess even of the calculated resistance of thin cylinders. The formulas for thick cylinders appear to be in error on the safe side; and very greatly so when, as is usually the case, the cylinder is short, and strengthened by having a head cast in. Such cylinders are generally also strengthened by very heavy flanges at the open end.

The Pressure allowed by Law or by government regulations on any cylindrical shell is found by the following rule:

"Multiply one sixth ($\frac{1}{6}$) of the lowest tensile strength found stamped on any plate in the cylindrical shell by the thickness—expressed in inches or parts of an inch—of the thinnest plate in the same cylindrical shell, and divide by the radius or half diameter—also expressed in inches—and the sum will be the pressure allowable per square inch of surface for single-riveting, to which add 20 per centum for double-riveting."

The hydrostatic pressure applied under the above table and rule must be in the proportion of 150 pounds to the square inch to 100 pounds to the square inch of the working pressure allowed.

The following table gives the pressures thus calculated for single-riveted boilers of various sizes:

TABLE OF PRESSURES ALLOWABLE ON BOILERS MADE SINCE FEBRUARY 28, 1872.

Diameter of Boiler.	Thickness of Plates.	45,000 Tensile Strength. 1/6, 7,500		50,000 Tensile Strength. 1/6, 8,333.3		55,000 Tensile Strength. 1/6, 9,166.6		60,000 Tensile Strength. 1/6, 10,000		65,000 Tensile Strength. 1/6, 10,833.3		70,000 Tensile Strength. 1/6, 11,666.6	
		Pressure.	20 per cent additional.	Pressure.	20 per cent additional.	Pressure.	20 per cent additional.	Pressure.	20 per cent additional.	Pressure.	20 per cent additional.	Pressure.	20 per cent additional.
36 Inches.	.1875	78.12	93.74	86.8	104.16	95.48	114.57	104.16	124.99	112.84	135.4	121.52	145.82
	.21	87.5	105.	97.21	116.65	106.94	128.3	116.66	139.99	126.38	151.65	136.11	163.33
	.23	95.83	114.99	106.47	127.76	117.12	140.54	127.77	153.32	138.41	166.09	149.07	178.88
	.25	104.16	124.99	115.74	138.88	127.31	152.77	138.88	166.65	150.46	180.55	162.03	193.43
	.26	108.33	129.99	120.37	144.44	132.4	158.88	144.44	173.32	156.48	187.77	168.51	202.21
	.29	120.83	144.99	134.25	161.11	147.68	177.21	161.11	193.33	174.53	209.43	187.90	225.48
	.3125	130.2	156.24	144.67	173.6	159.14	190.96	173.6	208.32	188.07	225.68	202.5	243.04
	.33	137.5	165.	152.77	183.32	168.05	201.66	183.33	219.99	198.61	238.33	213.88	256.65
	.35	145.83	174.99	162.03	194.43	178.23	213.87	194.44	233.32	210.64	252.76	226.84	272.20
	.375	156.25	187.5	173.61	208.33	190.97	229.16	208.33	249.99	225.69	271.82	243.05	291.66
38 Inches.	.1875	74.01	88.89	82.23	98.67	90.46	108.54	98.68	118.41	106.9	128.28	115.13	138.16
	.21	82.89	99.46	92.1	110.52	101.31	121.57	110.52	132.62	119.73	143.67	128.93	154.71
	.23	90.78	108.93	100.87	121.04	110.96	133.15	121.05	145.26	131.13	157.35	141.22	169.46
	.25	98.68	118.41	109.64	131.56	120.61	144.73	131.57	157.88	142.54	171.04	153.5	184.20
	.26	102.63	123.15	114.03	136.83	125.43	150.51	136.84	164.2	148.24	177.88	159.64	191.56
	.29	114.47	137.36	127.19	152.62	139.91	167.89	152.63	183.15	165.35	198.42	178.06	213.67
	.3125	123.35	148.02	137.	164.46	150.70	180.91	164.47	197.36	178.17	213.8	191.88	230.25
	.33	130.26	156.31	144.73	173.67	159.2	191.04	173.68	208.41	188.15	225.78	202.62	243.14
	.35	138.15	165.78	153.5	184.21	168.85	202.62	184.21	221.05	199.56	239.47	214.91	257.89
	.375	148.	177.60	164.73	197.67	180.81	217.09	197.36	236.83	213.81	256.57	230.26	276.31
40 Inches.	.1875	70.31	84.37	78.12	93.74	85.93	103.11	93.75	112.5	101.56	121.87	109.37	131.24
	.21	78.75	94.50	87.49	104.98	96.24	115.48	105.	126.	113.74	136.48	122.49	146.98
	.23	86.25	103.5	95.83	114.99	105.41	126.49	115.	138.	124.58	149.49	134.16	160.99
	.25	93.75	112.5	104.16	124.99	114.58	137.49	125.	150.	135.41	162.49	145.83	174.99
	.26	97.5	117.	108.33	129.99	119.16	142.99	130.	156.	140.83	168.99	151.66	181.99
	.29	108.75	130.5	120.83	144.99	132.91	159.49	145.	174.	157.08	188.49	169.16	202.99
	3125	117.18	140.61	130.2	156.24	143.22	171.86	156.25	187.45	169.27	203.12	182.29	218.74
	.33	123.75	148.5	137.49	164.98	151.24	181.48	165.	198.	178.74	214.48	192.49	230 98
	.35	131.25	157.5	145.83	174.99	160.41	192.49	175.	210.	189.58	227.49	204.16	244.99
	.375	140.62	168.74	156.24	187.48	171.87	206.24	187.5	225.	203.12	243.74	218.74	262.48
42 Inches.	.1875	66.96	80.35	74.40	89.28	81.84	98.20	89.28	107.13	96.72	116.06	104.16	124.99
	.21	75.	90.	83.32	99.99	91.66	109.99	100.	120.	108.33	129.99	116.66	139.99
	.23	82.14	98.56	91.23	109.51	100.39	120.46	109.52	131.42	118.65	142.38	127.77	153 32
	.25	89.28	107.13	99.2	119.04	109.12	130.94	119.04	142.84	128.96	154.75	138.88	166.65
	.26	92.85	111.42	103.17	123.8	113.49	136.18	123.8	148.56	134.12	160.94	144.44	173.32
	.29	103.57	124.28	115.07	138.08	126.57	151.85	138.09	165.7	149.6	179.52	161.11	193.33
	.3125	111.6	133.92	124.	148.8	136.4	163.68	148.74	178.56	161.2	193.44	173.61	208.23
	.33	117.85	141.42	130.94	157.12	114.04	172.84	157.14	188.56	170.23	204.27	183.33	219.99
	.35	125.	150.	138.88	166.65	152.77	183.32	166.66	199.99	180.55	216.66	194 44	233.32
	.375	133.92	160.7	148.8	178.56	163.68	196.40	178.57	214.28	193.45	232.14	208.33	249 99
44 Inches.	.1875	63.92	76.7	71.01	85.22	78.12	93.74	85.22	102.26	92.32	110.78	99.42	119.3
	.21	71.59	85.9	79.54	95.44	87.49	104.98	95.45	114.54	103.4	124.08	111.36	133.63
	.23	78.4	94.08	87.12	104.54	95.83	114.99	104.54	125.44	113.25	135.9	121.96	146.35
	.25	85.22	102.26	94.69	113.62	104.16	124.99	113.63	136.35	123.1	147.72	132.56	159.07
	.26	88.63	106.35	98.48	118.17	108.33	129.99	118.18	141.81	128.02	153.62	137.87	165.44
	.29	98.86	118.63	109.84	131.80	120.83	144.99	131.81	158.17	142.79	171.33	153.78	184.53
	.3125	106.53	127.83	118.36	142.03	130.2	156.24	142.04	170.44	153.88	184.65	165.71	198.85
	.33	112.5	135.	124.99	149.98	137.49	164.98	150.	180.	162.49	194.98	174.99	209.98
	.35	119.31	143.17	132.57	159.08	145.83	174 99	159.09	190.9	172.34	206.8	185.6	222.72
	.375	127.81	153.37	142.04	170.44	156.24	187.48	170.45	204.54	184.65	221.58	198.86	238.63

TABLE OF PRESSURES ALLOWABLE ON BOILERS MADE SINCE FEBRUARY 28, 1872.—*Continued.*

Diameter of Boiler.	Thickness of Plates.	45,000 Tensile Strength. ⅙, 7,500		50,000 Tensile Strength. ⅙, 8,333.3		55,000 Tensile Strength. ⅙, 9,166.6		60,000 Tensile Strength. ⅙, 10,000		65,000 Tensile Strength. ⅙, 10,833.3		70,000 Tensile Strength. ⅙, 11,666.6	
		Pressure.	20 per cent additional.	Pressure.	20 per cent additional.	Pressure.	20 per cent additional.	Pressure.	20 per cent additional.	Pressure.	20 per cent additional.	Pressure.	20 per cent additional.
46 Inches	.1875	61.14	73.36	67.93	81.51	74.72	89.66	81.51	97.81	88.31	105.97	95.1	114.12
	.21	68.47	82.16	76.08	91.29	83 69	100.42	91.3	109.56	98.91	118.69	106.52	127.82
	.23	75.	90.	83.33	100.	91.66	109.99	100.	120.	108.33	129.99	116.66	139.99
	.25	81.51	97.81	90.57	108.68	99.63	119.55	108.69	130.42	117.75	141.3	126.8	152.16
	.26	81.78	101.73	94.2	113.04	103.62	124.34	113.44	135.64	122.46	146.95	131.88	158.25
	.29	94.56	113.47	105 07	126.	115.57	138.68	126.09	151.3	136.59	163.92	147.1	176.52
	.3125	101.9	122.28	113.21	135.86	124.54	149.44	135.86	163 03	147.19	176.62	158.51	190.21
	.33	107.6	129.12	119.56	143.47	131.52	157.82	143 97	172.16	155.43	186.51	167.39	200.86
	.35	114.13	136.95	126.8	152.16	139.49	167.38	152.17	182.6	164.85	197.82	177.53	213.03
	.375	122.28	146.73	135.86	163.03	149.45	179.34	163.04	195.64	176.62	211.94	190.21	228.25
48 Inches.	.1875	58.59	70.30	65.1	78.12	71.61	85.93	78.12	93.74	84.63	101.55	91.13	109.35
	.21	65.62	78.74	72.91	87.49	80.2	96.24	87.49	104.98	94.79	113.74	102.08	122.49
	.23	71.87	86.24	79.85	95.82	87.84	105.4	95.83	114.99	103.81	124.57	111.8	133.16
	.25	78.12	93.74	86.8	104 16	95.48	114.57	104.16	124.99	112.84	135.4	121.52	145.82
	.26	81.25	97.50	90.27	108.32	99.3	119.16	108.33	129.99	117.36	140.83	126.38	151.65
	.29	90.62	108.74	100.69	120.82	110.76	132.91	120 83	144.99	130.9	157.08	140.97	169.16
	.3125	97.65	117.18	108.5	130.2	119.35	143.22	130.21	156.25	141.05	169.26	151.9	182.28
	.33	103.12	123.74	114.58	137.49	126.04	151.24	137.5	165.	148.95	178.74	160.41	192.49
	.35	109.37	131.24	121.52	145.82	133.67	160.4	145.83	174.99	157.98	189.57	170.13	204.15
	.375	117.18	140.61	130.2	156.24	143.22	171.86	156.25	187.50	169.27	203.12	182.29	218.74
54 Inches.	.1875	52.08	62.49	57.87	69.44	63.65	76.38	69.44	82.44	75.23	90.27	81.01	97.21
	.21	58.33	69.99	64.81	77.77	71.29	85.54	77.77	93.32	84.25	101.1	90.74	108.88
	.23	63.88	76.65	70.98	85.17	78.08	93.69	85.18	102.21	92.28	110.73	99.38	119.25
	.25	69.44	83.32	77.16	92.59	84.87	101.84	92.59	111.10	100.3	120.36	108.02	129.62
	.26	72.22	86.66	80.24	96.28	88.27	105.92	96.29	115.54	104.31	125.17	112.44	134.8
	.29	80.55	96.66	89.5	107.40	98.45	118.14	107.41	128.88	116.35	139.62	125.3	150.36
	.3125	86 8	104.16	96.44	115.72	106.09	127.30	115.55	138.66	125.38	150.45	135.03	162.03
	.33	91.66	109 99	101.84	122.22	112.03	134.43	122.22	146.66	132.4	158.88	142.59	171.10
	.35	97.22	116.66	108.02	129.62	118.82	142.58	120.62	155.54	140.43	168.51	151.23	181.47
	.375	104.16	124.99	115.74	138.88	127.31	152.77	138.88	166.65	150.46	180.55	162.03	194.43
60 Inches.	.1875	46.87	56.24	52.08	62.49	57.29	68.74	62.5	75.	67.7	81.24	72 91	87.49
	.21	52.5	63.	58.33	69.99	64.16	76.99	69.99	84.	75.83	90.99	81.66	97.99
	.23	57.5	69.	63.88	76.65	70.27	84.32	76.66	91.99	83.05	99.66	89.44	107.32
	.25	62.5	75.	69.44	83.32	76.38	91.65	83.33	99.99	90.27	108.32	97.22	116.66
	.26	65.	78.	72.22	86.66	79.44	95.32	86.66	103.99	93.88	112.65	101.11	121.33
	.29	72.5	87.	80.55	96.66	88.61	106.33	96.66	115.99	104.72	125.66	112.77	135.32
	.3125	78.12	93.74	86.8	104.16	95.48	114.57	104.18	124.99	112.95	135.54	121.52	145.82
	.33	82.5	99.	91.66	109.99	100.83	120.99	109.99	132.	119.16	142.99	128.33	153.99
	.35	87.5	105.	97.22	116.66	106.94	128.32	116.66	139.99	126.38	151.65	136.11	163.33
	.375	93.75	112.5	104.16	124.99	114.58	137.49	125.	150.	135.41	162.49	145.83	175.99
66 Inches.	.1875	42.61	51.13	47.34	56.8	52.07	62.49	56.81	68.17	61.55	73.86	66.28	79.53
	.21	47.72	57.26	53.	63.63	58.33	69.99	63.63	76.35	68.93	82.71	74.24	89.08
	.23	52.27	62.72	58.	69.69	63.88	76.65	69.69	83.62	75.5	90.6	81.31	97.57
	.25	56.81	68.17	63.13	75.75	69.44	83.32	75.75	90.90	82.07	98.48	88.37	106.04
	.26	59.09	70.9	65.65	78.78	72.22	86 66	78.78	94.53	85.35	102.42	91.91	110.29
	.29	65.90	79.08	73.23	87.87	80.55	96.66	87.87	105.44	95.2	114.24	102.52	123.02
	.3125	71.	85.2	78.91	94.69	86.89	104.16	94 69	113.62	102.58	123.09	110.47	132.56
	.33	75.	90.	83.33	99.99	91.66	109.99	99.99	120.	108.33	129.99	116.66	139.99
	.35	79.56	95.47	88.38	106.05	97.22	116.66	106.	127.27	114.89	137.86	123.73	148.47
	.375	85.22	102.26	94.69	113.62	104.16	124.99	113.62	136.34	123.1	147.72	132.57	159.08

TABLE OF PRESSURES ALLOWABLE ON BOILERS MADE SINCE FEBRUARY 28, 1872.—*Continued.*

Diameter of Boiler.	Thickness of Plates.	45,000 Tensile Strength. ⅙, 7,500		50,000 Tensile Strength. ⅙, 8,333.3		55,000 Tensile Strength. ⅙, 9,166.6		60,000 Tensile Strength. ⅙, 10,000		65,000 Tensile Strength. ⅙, 10,833.3		70,000 Tensile Strength. ⅙, 11,666.6	
		Pressure.	20 per cent additional.	Pressure.	20 per cent additional.	Pressure.	20 per cent additional.	Pressure.	20 per cent additional.	Pressure.	20 per cent additional.	Pressure.	20 per cent additional
	.1875	39.06	46.87	43.4	52.08	47.74	57.28	52.08	62.49	56.42	67.70	60.76	72.91
	.21	43.75	52.5	48.6	58.33	53.47	64.16	58.33	69.99	63.19	75.82	68 05	81.66
	.23	47.91	57.49	53.24	63.88	58.56	70.27	63.88	76.65	62.21	83.05	74.53	89.43
	.25	52.08	62.49	57.87	69.44	63.65	76.38	69.44	83.32	75.22	90.26	81.01	97.21
72 Inches.	.26	54.16	64.99	60.18	72.21	66.2	79.44	72.22	86.66	78 24	93 88	84.25	105.10
	.29	60.41	72.49	67.12	80.54	73.84	88.60	80.55	96.66	87.26	104.71	93.98	112.77
	.3125	65.10	78.12	72.33	86.8	79.57	95.48	86.8	104.16	94.03	112 83	101.27	121.52
	.33	68 75	82.5	76.38	91.65	84.02	100.82	91.66	109.99	99 3	119.16	106.94	128.32
	.35	72.91	87.49	81.01	97.21	89.11	106.93	97.22	116.66	105.32	126.38	113.42	136.1
	.375	78.12	93.74	86.8	104.16	95.48	114.57	104.16	124.99	112.84	135.43	121 52	145.82
	.1875	36.05	43.21	40.06	48.07	44.07	52.87	48.07	57.68	52.08	62.49	56.08	67.29
	.21	40.38	48.45	44.87	53.84	49.35	59.22	53.84	64.60	58.33	69.99	62.82	75.38
	.23	44.23	53.07	49.14	58.96	54.05	64.86	58.95	70.76	63.88	76.65	68.80	82.56
	.25	48.07	57.68	53.41	64.09	58.76	70.5	64.4	76.02	69.44	83.32	74.78	89 73
78 Inches.	.26	50.	60.	55.55	66.66	66.11	73.33	66.66	79.99	72.22	86.66	77.77	93 32
	.29	55 76	66.91	61.96	74.35	68.16	81.79	74.35	89.22	80 55	96.66	86.75	104.1
	.3125	60 09	72.1	66.77	80.12	73.45	88.14	80.12	96.14	86.8	104.16	93.48	112.17
	.33	63.46	76.15	70.51	84.61	77.56	93.07	84.61	101.53	91.66	109.99	98.71	118.45
	.35	67.3	80.76	74.78	89.73	82.26	98.71	89 74	107.68	97.22	116.66	104.70	125.64
	.375	72.11	86.53	80.12	96.14	88.14	105.76	96.15	115.38	104.16	124.99	112.17	134 6
	.1875	33.48	40.17	37.2	44.68	40.92	49 1	44.64	53.56	48.36	58.03	52.08	62.49
	.21	37.5	45.	41.66	49.99	45.83	54.99	50.	60.	54.16	64 99	58.33	69.99
	.23	41.02	49.22	45.63	54.75	50.19	60.22	54.75	65 71	59.32	71.18	63.65	76.38
	.25	44.64	53.56	49.6	59.52	54 56	65.47	59.52	71.42	64.48	77.37	69.44	83.32
84 Inches.	.26	46.42	55.7	51.58	61.89	56.74	68.08	61.9	74.28	67.05	80.46	72.22	86.66
	.29	51.78	62.13	57.53	69.03	63.29	75 94	69.04	82.84	74.8	89.76	80.55	96.66
	.3125	55.8	66.96	62.	74.4	68.2	81.84	74.4	89.28	80.6	96.72	86.8	104.16
	.33	58.92	70.7	65.47	78.56	72.02	86.42	78.57	94.28	85.11	102.13	91.66	109.99
	.35	62.5	75.	69.44	83.32	76.38	91.65	83.33	99.99	90.27	108.32	97.22	116.66
	.375	66.96	80.35	74.4	89.28	81.84	98.2	89.28	107.13	96.72	116.06	104 16	124.99
	.1875	31.25	37.5	34.72	41.66	38.19	45.82	41.66	49.99	45.13	54.15	48.68	58.33
	.21	35.	42.	38.88	46.65	42.77	51.32	46.66	55.99	50.55	60.66	54.44	65.32
	.23	38.33	45.99	42.59	51.10	46.85	56.22	51.11	61.33	55.37	66.44	59.62	71.54
	.25	41.66	49.99	46.29	55.54	50.92	61.1	55.55	66 66	60.18	72.21	64.81	77.77
90 Inches.	.26	43.33	51.99	48.14	57.76	52 96	63 55	57.77	69.32	62.59	75.1	67.4	80.88
	.29	48.33	57.99	53.7	64.44	59.07	70.8	64.44	77.32	69.81	83.77	75.18	90.21
	.3125	52.08	62.49	57.86	69.43	63.65	76.38	69.44	83.32	75.23	90.27	81.01	97.21
	.33	55.	66.	61.11	73.33	67.22	80.66	73.33	87.99	79.44	95.32	85.55	102.66
	.35	58.33	69 99	64.81	77.77	71.29	85.54	77.77	93.32	84.25	101.1	90.72	108.88
	.375	62.5	75.	69.44	83.32	76.38	91.65	83.33	99.99	90.27	108.32	97.22	116.66
	.1875	29.29	35.14	32.55	39.06	35 8	42.96	39.06	46.87	42.31	50.77	45.57	54.68
	.21	32.81	39.37	36.45	43.74	40.1	48.12	43.75	52.5	47.39	56.86	51.04	61.24
	.23	35.93	43.11	39.93	47.91	43.92	52.7	47.91	57.49	51.9	62.28	55.9	67.08
	.25	39.06	46.87	43.4	52.08	47.74	57.28	52.08	62.49	56.42	67.67	60.76	72.91
96 Inches.	.26	40.62	48.74	45.14	54.16	49.65	59.68	54.16	64.99	58.78	70.53	63.19	75.82
	.29	45.31	54.37	50.34	60.4	55.38	66.45	60.41	72.49	65.45	78.54	70.48	84.57
	.3125	48 82	58.58	54.25	65.1	59.67	71.6	65.1	78.12	70.52	84.62	75.95	91.14
	.33	51.56	61.87	57.29	68.74	63.02	75.62	68.75	82.5	74.47	89.36	80.2	96.24
	.35	54.68	65.61	60.76	72.91	66.83	80.19	72.91	87.49	78.99	94.78	85.06	102.07
	.375	58.58	70.29	65.1	78.12	71.61	85.93	78.12	93.74	84.63	101.55	91.14	109.6

TABLE OF PRESSURES ALLOWABLE ON BOILERS MADE SINCE FEBRUARY 28, 1872.—*Continued.*

Diameter of Boiler.	Thickness of Plates.	45,000 Tensile Strength. ⅙, 7,500		50,000 Tensile Strength. ⅙, 8,333.3		55,000 Tensile Strength. ⅙, 9,166.6		60,000 Tensile Strength. ⅙, 10,000		65,000 Tensile Strength. ⅙, 10,833.3		70,000 Tensile Strength. ⅙, 11,666.6	
		Pressure.	20 per cent additional.	Pressure.	20 per cent additional.	Pressure.	20 per cent additional.	Pressure.	20 per cent additional.	Pressure.	20 per cent additional.	Pressure.	20 per cent additional.
46 Inches	.1875	61.14	73.36	67.93	81.51	74.72	89.66	81.51	97.81	88.31	105.97	95.1	114.12
	.21	68.47	82.16	76.08	91.29	83 69	100.42	91.3	109.56	98.91	118.69	106.52	127.82
	.23	75.	90.	83.33	100.	91.66	109.99	100.	120.	108.33	129.99	116.66	139.99
	.25	81.51	97.81	90.57	108.68	99.63	119.55	108.69	130.42	117.75	141.3	126.8	152.16
	.26	81.78	101.73	94.2	113.04	103.62	124.34	113.44	135.64	122.46	146.95	131.88	158.25
	.29	94.56	113.47	105 07	126.	115.57	138.68	126.09	151.3	136.59	163.92	147.1	176.52
	.3125	101.9	122.28	113.21	135.86	124.54	149.44	135.86	163 03	147.19	176.62	158.51	190.21
	.33	107.6	129.12	119.56	143.47	131.52	157.82	143 97	172.16	155.43	186.51	167.39	200.86
	.35	114.13	136.95	126.8	152.16	139.49	167.38	152.17	182.6	104 85	197.82	177.53	213.03
	.375	122.28	146.73	135.86	163.03	149.45	179.34	163.04	195.64	176.62	211.94	190.21	228.25
48 Inches.	.1875	58.59	70.30	65.1	78.12	71.61	85.93	78.12	93.74	84.63	101.55	91.13	109.35
	.21	65.62	78.74	72.91	87.49	80.2	96.24	87.49	104.98	94.79	113.74	102.08	122.49
	.23	71.87	86.24	79.85	95.82	87.84	105.4	95.83	114.99	103.81	124.57	111.8	133.16
	.25	78.12	93.74	86.8	104 16	95.48	114.57	104.16	124.99	112.84	135.4	121.52	145.82
	.26	81.25	97.50	90.27	108.32	99.3	119.16	108.33	129.99	117.36	140.83	126.38	151.65
	.29	90.62	108.74	100.69	120.82	110.76	132.91	120.83	144.99	130.9	157.08	140.97	169.16
	.3125	97.65	117.18	108.5	130.2	119.35	143.22	130.21	156.25	141.05	169.26	151.9	182.28
	.33	103.12	123.74	114.58	137.49	126.04	151.24	137.5	165.	148.95	178.74	160.41	192.49
	.35	109.37	131.24	121.52	145.82	133 67	160.4	145.83	174.99	157.98	189.57	170.13	204.15
	.375	117.18	140.61	130.2	156.24	143.22	171.86	156 25	187.50	169.27	203.12	182.29	218.74
54 Inches.	.1875	52.08	62.49	57.87	69.44	63.65	76.38	69.44	82.44	75.23	90.27	81.01	97.21
	.21	58.33	69.99	64.81	77.77	71.29	85.54	77.77	93.32	84.25	101.1	90.74	108.88
	.23	63.88	76.65	70.98	85.17	78.08	93.69	85.18	102.21	92.28	110.73	99.38	119.25
	.25	69.44	83.32	77.16	92.59	84.87	101.84	92.59	111.10	100.3	120.36	108.02	129.62
	.26	72.22	86.66	80.24	96.28	88.27	105.92	96.29	115.54	104.31	125.17	112.44	134.8
	.29	80.55	96.66	89.5	107.40	98.45	118.14	107.41	128.88	116.35	139.62	125.3	150.36
	.3125	86 8	104.16	96.44	115.72	106.09	127.30	115.55	138.66	125.38	150.45	135.03	162.03
	.33	91.66	109 99	101.84	122.22	112.03	134.43	122.22	146.66	132.4	158.88	142.59	171.10
	.35	97.22	116.66	108.02	129.62	118.82	142.58	120.62	155.54	140.43	168.51	151.23	181.47
	.375	104.16	124.99	115.74	138.88	127.31	152.77	138.88	166.65	150.46	180.55	162.03	194.43
60 Inches.	.1875	46.87	56.24	52.08	62.49	57.29	68.74	62.5	75.	67.7	81.24	72 91	87.49
	.21	52.5	63.	58.33	69.99	64.16	76.99	69.99	84.	75.83	90.99	81.66	97.99
	.23	57.5	69.	63.88	76.65	70.27	84.32	76.66	91.99	83.05	99.66	89.44	107.32
	.25	62.5	75.	69.44	83.32	76.38	91.65	83.33	99.99	90.27	108.32	97.22	116.66
	.26	65.	78.	72.22	86.66	79.44	95.32	86.66	103.99	93.88	112.65	101.11	121.33
	.29	72.5	87.	80.55	96.66	88.61	106.33	96.66	115.99	104.72	125.66	112.77	135.32
	.3125	78.12	93.74	86.8	104.16	95.48	114.57	104.18	124.99	112.95	135.54	121.52	145.82
	.33	82.5	99.	91.66	109.99	100.83	120.99	109.99	132.	119.16	142.99	128.33	153.99
	.25	87.5	105.	97.22	116.66	106.94	128.32	116.66	139.99	126.38	151.65	136.11	163.33
	.375	93.75	112.5	104.16	124.99	114.58	137.49	125.	150.	135.41	162.49	145.83	175.99
66 Inches.	.1875	42.61	51.13	47.34	56.8	52.07	62.49	56.81	68.17	61.55	73.86	66.28	79.53
	.21	47.72	57.26	53.	63.63	58.33	69.99	63.63	76.35	68.93	82.71	74.24	89.08
	.23	52.27	62.72	58.	69.69	63.88	76.65	69.69	83.62	75.5	90.6	81.31	97.57
	.25	56.81	68.17	63.13	75.75	69.44	83.32	75.75	90.90	82.07	98.48	88.37	106.04
	.26	59.09	70.9	65.65	78.78	72.22	86 66	78.78	94.53	85.35	102.42	91.91	110.29
	.29	65.90	79.08	73.23	87.87	80.55	96.66	87.87	105.44	95.2	114.24	102.52	123.02
	.3125	71.	85.2	78.91	94.69	86.80	104.16	94 69	113.62	102.58	123.09	110.47	132.56
	.33	75.	90.	83.33	99.99	91.66	109.99	99.99	120.	108.33	129.90	116.66	139.99
	.35	79.56	95.47	88.38	106.05	97.22	116.66	106.	127.27	114.89	137.86	123.73	148.47
	.375	85.22	102.26	94.69	113.62	104.16	124.99	113.62	136.34	123.1	147.72	132.57	159.08

TABLE OF PRESSURES ALLOWABLE ON BOILERS MADE SINCE FEBRUARY 28, 1872.—*Continued.*

Diameter of Boiler.	Thickness of Plates.	45,000 Tensile Strength. ⅙, 7,500		50,000 Tensile Strength. ⅙, 8,333.3		55,000 Tensile Strength. ⅙, 9,166.6		60,000 Tensile Strength. ⅙, 10,000		65,000 Tensile Strength. ⅙, 10,833.3		70,000 Tensile Strength. ⅙, 11,666.6	
		Pressure.	20 per cent additional.	Pressure.	20 per cent additional.	Pressure.	20 per cent additional.	Pressure.	20 per cent additional.	Pressure.	20 per cent additional.	Pressure.	20 per cent. additional
	.1875	39.06	46.87	43.4	52.08	47.74	57.28	52.08	62.49	56.42	67.70	60.76	72.91
	.21	43.75	52.5	48.6	58.33	53.47	64.16	58.33	69.99	63.19	75.82	68 05	81.66
	.23	47.91	57.49	53.24	63.88	58.56	70.27	63.88	76.65	62.21	83.05	74.53	89.43
	.25	52.08	62.49	57.87	69.44	63.65	76.38	69.44	83.32	75.22	90.26	81.01	97.21
72 Inches.	.26	54.16	64.99	60.18	72.21	66.2	79.44	72.22	86.66	78 24	93 88	84.25	105.10
	.29	60.41	72.49	67.12	80.54	73.84	88.60	80.55	96.66	87.26	104.71	93.98	112.77
	.3125	65.10	78.12	72.33	86.8	79.57	95.48	86.8	104.16	94 03	112 83	101.27	121.52
	.33	68 75	82.5	76.38	91.65	84.02	100.82	91.66	109.99	99 3	119.16	106.94	128.32
	.35	72.91	87.49	81.01	97.21	89.11	106.93	97.22	116.66	105.32	126.38	113.42	136.1
	.375	78.12	93.74	86.8	104.16	93.48	114.57	104.16	124.99	112.84	135.43	121.52	145.82
	.1875	36.05	43.21	40.06	48.07	44.07	52.87	48.07	57.68	52.08	62.49	56.08	67.29
	.21	40.38	48.45	44.87	53.84	49.35	59.22	53.84	64 60	58.33	69.99	62.82	75.38
	.23	44.23	53.07	49.14	58.96	54.05	64.86	58.95	70.76	63.88	76.65	68.80	82.56
	.25	48.07	57.68	53.41	64.09	58.76	70.5	64.4	76.92	69.44	83.32	74.78	89 73
78 Inches.	.26	50.	60.	55.55	66.66	66.11	73.33	66.66	79.99	72.22	86.66	77.77	93 32
	.29	55 76	66.91	61.96	74.35	68.16	81.79	74.35	89.22	80 55	96.66	86.75	104.1
	.3125	60 09	72.1	66.77	80.12	73.45	88.14	80.12	96.14	86.8	104.16	93.48	112.17
	.33	63.46	76.15	70.51	84.61	77.56	93.07	84 61	101.53	91.66	109.99	98.71	118.45
	.35	67.3	80.76	74.78	89.73	82.26	98.71	89 74	107.68	97.22	110.66	104.70	125.64
	.375	72.11	86.53	80.12	96.14	88.14	105.76	96.15	115.38	104.16	124.99	112.17	134 6
	.1875	33.48	40.17	37.2	44.68	40.92	49 1	44.64	53.56	48.36	58.03	52.08	62.49
	.21	37.5	45.	41.66	49 99	45.83	54.99	50.	60.	54.16	64 99	58.33	69.99
	.23	41.02	49.22	45.63	54.75	50.19	60.22	54.75	65 71	59.32	71.18	63.65	76.38
	.25	44.64	53.56	49.6	59.52	54 56	65.47	59.52	71.42	64.48	77.37	69.44	83 32
84 Inches.	.26	46.42	55.7	51.58	61.89	56.74	68.08	61.9	74.28	67.05	80.46	72.22	86.66
	.29	51.78	62.13	57.53	69.03	63.29	75 94	69.04	82.84	74.8	89.76	80.55	96.66
	.3125	55.8	66.96	62.	74.4	68.2	81.84	74.4	89.28	80.6	96.72	86.8	104.16
	.33	58.92	70.7	65.47	78.56	72 02	86.42	78.57	94.28	85.11	102.13	91.66	109.99
	.35	62.5	75.	69.44	83.32	76.38	91.65	83.33	99.99	90.27	108.32	97.22	116.66
	.375	66.96	80.35	74 4	89.28	81.84	98.2	89.28	107.13	96.72	116.06	104 16	124.99
	.1875	31.25	37.5	34.72	41.66	38.19	45.82	41.66	49.99	45.13	54.15	48.68	58.33
	.21	35.	42.	38.88	46.65	42.77	51.32	46.66	55.99	50.55	60.66	54.44	65.32
	.23	38.33	45.99	42.59	51.10	46.85	56.22	51.11	61.33	55.37	66.44	59.62	71.54
	.25	41.66	49.99	46.29	55.54	50.92	61.1	55.55	66 66	60.18	72.21	64.81	77.77
90 Inches.	.26	43.33	51.99	48.14	57.76	52 96	63 55	57.77	69.32	62.59	75.1	67.4	80.88
	.29	48.33	57.99	53.7	64.44	59.07	70.8	64.44	77.32	69.81	83.77	75.18	90.22
	.3125	52.08	62.49	57.86	69.43	63.65	76.38	69.44	83.32	75.23	90 27	81.01	97.21
	.33	55.	66.	61.11	73.33	67.22	80.66	73.33	87.99	79.44	95.32	85.55	102.66
	.35	58.33	69 99	64.81	77.77	71.29	85.54	77.77	93.32	84.25	101.1	90.72	108.88
	.375	62.5	75.	69.44	83.32	76.38	91.65	83.33	99.99	90.27	108.32	97.22	116.66
	.1875	29.29	35.14	32.55	39.06	35 8	42.96	39.06	46.87	42.31	50.77	45.57	54.68
	.21	32.81	39.37	36.45	43.74	40.1	48.12	43.75	52.5	47.39	56.86	51.04	61.24
	.23	35.93	43.11	39.93	47.91	43 92	52.7	47.91	57.49	51.9	62.28	55.9	67.08
	.25	39.06	46.87	43.4	52.08	47.74	57.28	52.08	62.49	56.42	67.67	60.76	72.91
96 Inches.	.26	40.62	48.74	45.14	54 16	49.65	59.68	54.16	64.99	58.78	70.53	63.19	75.82
	.29	45.31	54.37	50.34	60.4	55.38	66.45	60 41	72.49	65.45	78.54	70.48	84.57
	.3125	48 82	58.58	54.25	65.1	59.67	71.6	65.1	78.12	70.52	84.62	75.95	91.14
	.33	51.56	61.87	57.29	68.74	63.02	75.62	68.75	82.5	74.47	89.36	80.2	96.24
	.35	54.68	65.61	60.76	72.91	66.83	80.19	72.91	87.49	78.90	94 78	85.06	102.07
	.375	58.58	70.29	65.1	78.12	71.61	85.93	78.12	93 74	84.63	101.55	91.14	109.6

Externally-fired boilers are not permitted by United States regulations to be made thicker than 0.51 inch (1.2 cm.). The 20 per cent higher pressure of the table is allowed on steam-vessels which carry no passengers. It will be observed that the rule above given allows an apparent "factor of safety" of six; while the loss of strength at a single-riveted seam reduces it to the actual value of four, nearly. It would probably be on the whole wiser to use as the actual value the higher figure, and thus to reduce the pressures carried to one third below those now permitted, except where inspection and test during construction, and constant supervision with frequent inspection during the life of the boiler, may give a safe margin with the lower figure. The operation of the law which allows old boilers to carry two thirds the test pressure is to reduce the real factor often to less than one and a half; for it is well known that iron will not carry permanently a load which it will sustain for a short time without observable yielding.

French regulations make the thickness of wrought-iron cylindrical shells of boilers not less than

$$t = 1.8pd + 3$$

in millimetres, when the pressure, p, is in atmospheres and the diameter, d, is in metres. In no case, however, is a greater thickness allowed than 15 mm. (0.6 in.).

German regulations give

$$t = 0.0015pd + 0.1 \text{ inches.}$$

Flues and Cylinders subjected to external pressure resist that pressure in proportion to their stiffness and their compressive strength if thin, and if thick sustain a pressure proportional to their thickness and maximum resistance to crushing.

Fairbairn,* experimenting on flues of thin iron, 0.04 inch

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* Useful Information. Second Series.

(0.102 centimetre), of small diameter, 4 inches (10.2 centimetres) to 12 (31 centimetres), and from 20 inches (50.8 centimetres) to 5 feet (1.52 metres) long, found that their resistance to collapse varied inversely as the product of their lengths and their diameters, and directly as the 2.19 power of their thickness.

The following equation fairly expressed his results when p is the external pressure in pounds per square inch, t their thickness in inches, d their diameter, and L the length in feet:

$$t = \sqrt[2.19]{\frac{pdL}{806,000}}; \quad p = 806,000\frac{t^{2.19}}{dL}; \quad . \quad . \quad . \quad . \qquad (1)$$

or, for the length in inches,

$$p = 9,672,000\frac{t^{2.19}}{dl}. \quad . \quad . \quad . \quad . \quad . \quad . \quad . \qquad (2)$$

In metric measures, kilogrammes and centimetres diameter, and metres of length,

$$p = 68,000\frac{t^{2.19}}{dL}, \text{ nearly.} \quad . \quad . \quad . \quad . \quad . \qquad (3)$$

$$t = \sqrt[2.19]{\frac{pdL}{68,000}}. \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \qquad (4)$$

For elliptical flues take $d = \frac{2a^2}{b}$; where a is the greater and b the lesser semi-axis.

These equations probably give too small values of t for heavy flues under high pressure.

Belpaire's rule, deduced from Fairbairn's experiments, is

$$p = 1,057,180\frac{t^{2.081}}{l^{0.564}d^{0.889}}. \quad . \quad . \quad . \quad . \quad . \quad . \qquad (5)$$

Lloyd's rule for flues is

$$p = \frac{at^2}{Ld}, \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (6)$$

in which a is made 89,600 pounds per square inch.

The *British Board of Trade Rule* is, for cylindrical furnaces with butted joints,

$$p = \frac{at^2}{(L+1)d}, \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (7)$$

in which a is 90,000, provided, always,

$$p < 8{,}000\frac{t}{d};$$

and for large joints $a = 70{,}000$, unless bevelled to a true circle, when $a = 80{,}000$. If the work is not of the best quality, these values of a are reduced to 80,000, 60,000, and 70,000.

Flanged and Corrugated Flues are much stronger than plain, lapped, or butt-jointed flues. Experiment indicates that it is allowable to consider the length L in the formulæ for strength of flues as the distance from flange to flange, and to assume that the flanges support the flue as effectively as the flue sheets. Where the several courses of a flue are flanged together instead of being connected by the usual lap-jointed girth-seams, the strength of the flue is thus enormously increased. Another method of strengthening the flue is by surrounding it, at intervals, with a strongly made ring of angle or T-iron, which answers the purpose of a flange, while being less costly in construction. To prevent injury by overheating at those parts where the total thickness of metal traversed by the heat from the furnace-gases would be objectionably great, the ring is often supported clear of the flue by a set of thimbles through which the rivets holding it in place are driven.

The corrugated flue is now very extensively used, the corrugations extending around the flue and having a pitch of ten

or twelve times the thickness of the sheet. These flues possess the double advantage of having more than twice the strength of equally heavy plain flues, and of being so much thinner for a given strength as to be vastly safer against overheating and burning. These flues are less liable to distortion in the processes of working than are plain flues.

By the United States regulations, lap-welded flues less than 18 feet long and 7 inches or more in diameter are allowed to carry pressures determined by the formula

$$p = \frac{ct}{r}; \quad t = \frac{pr}{c};$$

in which the pressure, p, is in pounds per square inch; the thickness, t, and the radius, r, of the flue in inches. The value of the constant c is 4400. This gives, for example, an allowable pressure of 200 pounds per square inch on a flue 14 inches in diameter, less than 18 feet long and 0.32 thick. A minimum thickness is set at

$$t = \text{diam.} \times 0.022.$$

For lap-welded flues exceeding 18 feet in length, 3 pounds is deducted from the pressure calculated as above, for each added foot, or 0.01 inch is added to its thickness. When between 7 and 16 inches diameter and 5 to 10 feet long, one strengthening ring is required; and where 10 to 15 feet long, two such rings, each of a thickness of metal at least equal to that of the flue, and 2½ inches or more in width.

Flues 16 to 40 inches diameter are allowed by the United States regulations a pressure

$$p = \frac{ft}{c},$$

in which $f = \frac{1760}{d}$, $c = 0.31$, or

$$p = 5678\frac{t}{d},$$

which allows 100 pounds per square inch on a flue 20 inches in diameter and 0.37 inch thick.

Corrugated furnace-flues are allowed to "carry" a pressure,

$$p = 14{,}000\frac{t}{d};$$

equivalent to 175 pounds on a flue 40 inches in diameter and 0.5 inch thick. Other flues are allowed pressures determined by Fairbairn's formula,

$$p = 89{,}600\frac{t^2}{Ld},$$

in which, however, L is in feet. Rings are fitted in such manner as to reduce the maximum tension on the rivets to 6000 pounds per square inch of section.

57. **Stayed Surfaces and Stays and Braces** are parts and members which, in steam-boiler design and construction, should be studied with special care. Where it is possible to make the strength of the structure ample by correctly forming parts exposed to stress, as by making them cylindrical, it is usually considered best to do so; but in many types of boiler this is impracticable, and staying must be resorted to. Properly designed stayed surfaces should be made the strongest parts of the boiler. The fireboxes of locomotives and of other firebox boilers, in which stay-bolts are well distributed, the water-legs of many marine boilers, and other parts composed of flat surfaces sustained by stays and braces, are common illustrations of the method of resisting pressure.

Where flat surfaces are secured against lateral pressure by stay-bolts, as is done in steam-boilers, these bolts may yield either by breaking across, or by shearing the threads of the screw in the bolt or in the sheet. Such bolts should not be so proportioned that they are equally liable to break by either method, but should be given a large factor of safety (15 to 20) to allow for reduction of size by corrosion, from which kind of deterioration they are liable to suffer seriously. Wrought-iron

and soft steels are used for these bolts. They are screwed through the plate, and the projecting ends are usually headed like rivets. Nuts are sometimes screwed on them instead of riveting them when they are not liable to injury by flame.

"Button-set" heads are from .25 to .35 stronger than the conical hammered head, and nuts give still greater strength.

Experiments made by Chief Engineers Sprague and Tower, for the U. S. Navy Department, lead to the following formula* and values of the coefficient a, p being the safe working pressure, t the thickness of plate, and d the distance from bolt to bolt:

$$p = a\frac{t^2}{d^2}. \qquad (1)$$

VALUES OF a IN BRITISH AND METRIC MEASURES.

	A.	A_m.
For iron plates and bolts	24,000	1,693
For steel plates and iron bolts	25,000	1,758
For steel plates and steel bolts	28,000	1,968
For iron plates and iron bolts with nuts	40,000	2,812
For copper plates and iron bolts	14,500	1,020

The working load is given in pounds on the square inch and kilogrammes per square centimetre, the measurements being taken in inches and centimetres. The heads, where riveted, are assumed to be made of the button shape.

The diameter of stay is made about $2\sqrt{t}$, the number of threads per inch 12, or 14 (5 or 6 per centimetre). A very high factor of safety, as above, is recommended for stays, to afford ample margin for loss by corrosion.

Lloyd's Rule for stayed plates is

$$p = \frac{at_1^2}{p_1^2}, \qquad (2)$$

in which p is the working pressure in pounds on the square inch, t_1 the thickness of plate in sixteenths of an inch, and p_1 is the distance apart of the stays in inches.

* Report on Boiler Bracing. Washington, 1879.

The coefficient a has the following value:

$a = 90$ for plate $\frac{7}{16}$ inch thick or less; with screw stays and riveted heads;
$a = 100$ for plate $\frac{7}{16}$ inch thick or more; screw stays and riveted heads;
$a = 110$ for plate $\frac{7}{16}$ inch thick or less; screw stays and nuts;
$a = 120$ for plate $\frac{7}{16}$ inch thick or more; screw stays and nuts;
$a = 140$ for plate $\frac{7}{16}$ inch thick or more; screw stays with double nuts;
$a = 160$ for plate $\frac{7}{16}$ inch thick; with screw stays double nuts and washers.

The Board of Trade of Great Britain prescribes

$$p = \frac{a(t_1 + 1)^2}{s - 6}, \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (3)$$

in which t_1 is the thickness of plate as above, and s is the area of surface supported, in square inches.

$a = 100$ for plates not exposed to heat, and fitted with nuts and washers of 3″ diameter and of $\frac{2}{3}$ the thickness of the plates;
$a = 90$ for same case, but with nuts only;
$a = 60$ in steam and having nuts and washers;
$a = 54$ if with nuts only;
$a = 80$ in water spaces, with screw stays and nuts;
$a = 60$ if with screw stays riveted;
$a = 36$ in steam, screw stays, riveted.

For girder stays,

$$p = \frac{ad_1^2t_1^2}{(w - p_1)d_2l}, \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (4)$$

where the symbols are defined as on page 148. When one,

two or three, or four bolts carry the girder, $a = 500$, 750, and 800, respectively.

Stay-bolts should have diameters considerably exceeding double the thickness of the plate.

D. K. Clark allows, as a maximum, the pressure

$$p = 407\frac{tT}{d}, \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (5)$$

where t, T, and d are the thickness of sheet and its tenacity, in tons per square inch, and the "pitch" of the stays in inches.

In computing the strength of stayed surfaces, it is to be understood that each stay sustains the pressure on an area bounded by lines drawn midway between it and its neighbors, and measured by the product of the distances between stays in the two directions of the lines of their attachments to the sheet. Thus marine boiler stays spaced 8 inches apart sustain the pressure on 64 square inches; while locomotive firebox stay-bolts spaced $4\frac{1}{2}$ inches each way carry the pressure on $20\frac{1}{4}$ square inches.

A common minimum factor of safety for stays, stay-bolts, and braces is 8, and when liable to serious corrosion the load applied is often reduced to 3000 or 4000 pounds per square inch of section of stay or brace, thus giving a factor of ten or more. The actual rupture of stay-bolted surfaces was found by the Author, by the study of the results of experimental steam-boiler explosions in 1871,* to be about the pressure

$$p = \left(365\frac{t}{d}\right)^2; \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (6)$$

in which t is the thickness of plate, and d the pitch of the stay-bolts. In design, we would make

$$\frac{365t}{\sqrt{ap'}}, \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (7)$$

* Journal Franklin Institute, 1872.

a being the factor of safety, which, as has been seen, should always be large, and p' the working pressure.

Fairbairn showed that the diameter of a stay-bolt should exceed double the thickness of the sheet by the amount to be allowed for corrosion. He found that riveting over the ends of screwed stays increased the strength of the construction 14 per cent.

Where the crown-sheet of the furnace of a boiler is supported by girders, the load to be permitted may be adjusted by the formula, already given,

$$p = \frac{cd^2t}{(w - p')d'l};$$

in which

w = width of the fire-box;
p' = the pitch of the supporting bolts;
d' = the distance from centre to centre of girders;
l = their length;
d = their depth;
t = their thickness;

all dimensions in inches except l, which is taken in feet. This is the formula approved by the British Board of Trade. The value of the coefficient c is from 500, when but one supporting bolt is used, to 750 and 800 when two or three and when four bolts are employed.

The accompanying figure exhibits a common form of stay for water-legs and other narrow water spaces. The stay is cut from a long screwed rod, and is frequently fitted with a nut and washer at each end. They are sometimes drilled longitudinally in order that they may give warning by leakage if fractured.

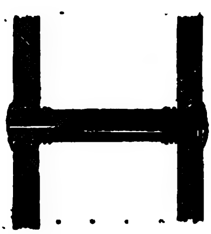

Fig. 68.

58. The Relative Strength of Shell and "Sectional" Boilers, and consequently, in large degree, their relative safety, "is measured by the relative magnitude of their largest parts. As remarked by John Stevens,

the inventor, the sectional boiler, with its smaller members and subdivided steam and water chambers, is safe in proportion as the sizes of the latter are diminished; while the large shells of the common forms of boiler are liable to dangerous rupture in proportion as their diameters are increased. The strengths of cylindrical reservoirs subjected to internal pressure, as are the shells, steam-drums, and mud-drums of shell boilers, and the tubes and steam-reservoirs of sectional boilers, are subject to laws so simple, and are computed by methods of such easy application, that there never need be any doubt in regard to the margin of safety existing in either case when new. Flues and old boiler-shells are less amenable to calculation, and are thus more unsafe. Water-tubular boilers are comparatively safe under all conditions of ordinary operation, and, when compared with the other type of steam-generator, are vastly safer.

59. **A Loss of Strength and of Ductility** is very often observed in the iron of which boilers are composed, as they advance in age, due to the progress of oxidation, probably, within and between the laminæ of which the sheets may be composed. The plate may be thus very nearly destroyed, at times, before this action may be detected. In some cases the iron may be nearly all destroyed, and only a sheet of oxide may remain; while the boiler, if not working under high pressure, may still appear sound. Such deterioration is often a source of great danger.

Excessively high temperature not infrequently gives rise to a loss of tenacity of serious amount with, fortunately, in most cases, increase of ductility. This is not invariably the case, however, as, at a "black heat" just below redness, a critical temperature is reached at which the iron may exhibit great brittleness.

The physical conditions thus modifying strength have been already described at considerable length. These changes occur in steam-boilers through the action of a variety of special causes. Ordinary oxidation, general and local, especially when accelerated by voltaic action, produces in many cases rapid deterioration; the constant and often great changes of temperature due to not only the ordinary working of the boiler, but also

at times to overheating of parts exposed to flame, may produce still more formidable effects; and even the continual changing of form caused by variations both of pressure and temperature, after the lapse of considerable periods of time, may give rise to important losses of ductility, and sometimes of strength. Steel is especially liable, if too hard, to loss of quality and dangerous injury by cracking, in consequence of such action.

60. The Deterioration of Boilers with age and with use is in nearly all cases due to modification of quality of metal, and to reduction of section of parts exposed to stress and strain. This deterioration is certain to occur to a greater or less extent; but its rate is usually indeterminate, and it consequently happens that, except by actual inspection and test, it is impossible to know, at any time after a boiler is built and set in operation, just what is its strength and whether it is safe.

This deterioration may be to a certain extent controlled and retarded by care and by the adoption of proper precautions. The principal requisite is the keeping of every part dry, and at a temperature below that of "burning" or rapid oxidation. Loss of strength, elasticity, ductility, and resilience will, however, always take place; and the boiler, whether in use or not, should always be very carefully examined at such intervals as shall insure its condition being known at all times, and such as shall secure a safe adjustment of the pressure maintained within it to its reduced strength. Every element and member of the structure will inevitably depreciate, and the most insignificant part must be kept under proper supervision to insure safe operation.

Experiment has shown that steel boiler-plate, exposed to repeated heating to high temperatures, and cooling down again, loses less by oxidation than does iron,* and retains its quality better. Steel loses rather more than iron when exposed to the action of sea-water,† and should never, if it can be conveniently avoided, be placed under such circumstances in contact with iron. Its own scale also produces an acceleration of galvanic

* *Engineering*, April 20, 1883.
† Trans. Inst. Naval Architects, vol. xxiii. p. 143.

action, and it is best, where practicable, to remove all the scale by "pickling" in dilute hydrochloric acid or in sal ammoniac.

61. Inspection and Test of boilers, at regular intervals and by methods that are thoroughly reliable, is now universally recognized as not only essential to permanent safe use of steam-generators, but also as necessary to secure maximum efficiency in their operation.

Such examinations and tests are usually made by expert inspectors who make a business of that work, and who have thus acquired exceptional, sometimes most extraordinary, skill in the detection of injury and its cause. The methods pursued and the rules adopted will be given later, in chapters devoted to the description of the methods of construction and to the prescription of forms of specification and contracts, and of the requisites of full conformance with the latter.

CHAPTER III.

THE FUELS AND THEIR COMBUSTION.

62. **The Chemical and Physical Principles** involved in the combustion of fuel, the development of heat and its transfer, are all well known and capable of very definite expression.

Combustion may be defined as the rapid combination of any oxidizable substance with oxygen. The result of such combination is the production of new compounds of definite character, and in quantities readily calculable when the amount of each of the combustible constituents is given. It is also known, very precisely, how much heat is produced by the combustion of any given weight of any one of the more familiar combustibles, and how much of that heat is available for transfer to a steam-boiler or other apparatus of utilization, when the combustion is complete and perfect.

Perfect combustion occurs when all of the combustible is burned, and with the result of producing the highest stage of oxidation. Carbon is perfectly burned when it is wholly converted into carbon dioxide and carbonic acid. Wood, or other fuel containing hydrogen, is perfectly consumed when all its carbon is oxidized to carbonic acid, and all its hydrogen is united with oxygen to form steam.

Chemical combination invariably produces heat, and decomposition as inevitably results in the absorption of heat in precisely the amount due to the opposite process. If both combination and decomposition take place in complex chemical changes, the heat produced is the net result of both actions.

Several interesting and important principles are recognized by writers on this general subject, as controlling the development of heat by combustion. Berthelot first called attention to the fact that the total heat evolved in any case of chemical

combustion is a measure of the energy expended in the separation of the resulting compound into its elements. The same chemist announced a second law, also known by his name: The quantity of heat-energy evolved or absorbed in any chemical change of this kind, where no mechanical work is done, is dependent purely on the initial and final states, and not at all on the intermediate process of change. Thus the heat produced in a furnace depends on the final product of combustion, and not at all on whether the carbon, for example, has been, at intermediate stages, wholly or partly burned, and has existed in greater or less proportion in the state of carbon monoxide or of carbon dioxide. Berthelot's third law asserts that in any chemical action the tendency is toward that method of change which will yield the greatest amount of heat. In other words, the tendency always exists to produce complete transformation of potential into actual energy.

63. **The Fuels used in Engineering*** are anthracite and bituminous coals, coke, wood, charcoal, peat, and combustible gases obtained by the distillation of the solid kinds of fuel. The oils—animal, vegetable, and mineral—and the solid hydrocarbons, of which bitumen is a type, are occasionally used also. All consist of either pure carbon or of combinations of carbon, hydrogen, and non-combustible substances. The mineral oils and liquid fuels generally promise excellent results when satisfactory methods shall have been found to secure the conditions of perfect combustion. In making a selection of a fuel the engineer is aided greatly by a knowledge of the origin and general characteristics of those combustibles from which he may be called upon to select the one best adapted to any given case.

Each form of fuel, solid, liquid, and gaseous, is specially adapted to particular purposes; and in selection the engineer and metallurgist should carefully examine all of the circumstances of the case under consideration, in order to determine from which of these classes the fuel required should be selected;

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* Adapted largely from the Author's "The Materials of Engineering," vol. i. N. Y.: J. Wiley & Sons, 1885.

and, this choice having been made, he will next select that *quality* which best fulfils the requirements of the case.

COMPOSITION OF COMBUSTIBLES, CARBON TAKEN AS 100.

	Carbon.	Hydrogen.	Oxygen.
Wood	100	12.48	83.07
Peat	100	9.85	55.67
Lignite	100	8.37	42.42
Bituminous Coal	100	6.12	21.23
Anthracite Coal	100	2.84	1.74

Coal, whether anthracite or bituminous, is a fossil of vegetable origin. It is always associated with some earthy matter, and the latter is sometimes present in such quantities as to destroy the value of the coal as a fuel.

Coal is sometimes found so slightly altered as to differ but little in chemical composition and in physical structure from recent vegetable substances; and in other cases it is so thoroughly changed as to have become, in all but its chemical constitution, a mineral. Some of the more completely fossilized bituminous coal breaks into cubic and rhomboidal fragments, but the anthracite exhibits little or no traces of crystallization.

Chemical examination shows coal, as already indicated, to be composed of both organic and inorganic matter. The former is purely vegetable, and the latter consists of earthy matter above which the ligneous portions once grew.

Destructive distillation resolves the organic matter into its invariable ultimate constituents, carbon, hydrogen, and oxygen, which come from the retort as solid carbon, or coke, liquid tar, gaseous ammonia, benzole, naphtha, paraffine, illuminating gas, sulphurous acid, and other substances, in various proportions. The inorganic portion is left as an ash when the fuel is burned. It consists usually of silicates in varying proportions.

The various fossil fuels having had a common origin, and being all more or less decomposed and mechanically altered vegetable matter, are found to exist in all states intermediate between that of recent vegetation and that of completely mineralized graphitic anthracite.

Their classification is therefore an arbitrary one, and it frequently happens that a particular species of coal lies so exactly between two classes as to make it difficult to determine to which it should be assigned.

The anthracites are found among the older carboniferous strata; the bituminous coals come from the secondary, and the softest and least altered varieties from the tertiary, formations.

The following, representing approximately the gradual change of composition as fossilization affects the alteration of woody fibre, is given by Dr. Wagner:

CHANGE OF COMPOSITION OF FOSSIL FUELS.

	Carbon.	Hydrogen.	Oxygen.
Cellulose	52.65	5.25	42.10
Peat	60.44	5.96	33.60
Lignite	66.96	5.27	27.76
" (earthy brown coal)	74.20	5.89	19.90
Coal (secondary)	76.18	5.64	18.07
" "	90.50	5.05	4.40
Anthracite	92.85	3.96	3.19

In the above analyses earthy matter is excluded.

64. **Anthracite Coal,** called sometimes *glance*, and sometimes *blind* or *stone coal*, consists of carbon and inorganic substances, and is usually free from hydrocarbons. Some varieties are thoroughly mineralized and have become graphitic. The ordinary varieties of good anthracite are hard, compact, lustrous, and sometimes iridescent. The color is intermediate between jet black and that of plumbago.

It is amorphous and somewhat vitreous in structure, the hardest varieties falling to pieces when suddenly heated, and sometimes breaking up into very small fragments, thus causing considerable loss even when carefully "fired." It sometimes gives out a ringing sound when struck. It is a strong, dense coal, its specific gravity ranging from 1.4 to 1.6. It has a high colorific value.

It burns without smoke and without flame unless containing moisture, the vapor of which produces a yellow flame of comparatively low temperature. It kindles slowly and with dif-

ficulty; and, once kindled, requires to be carefully and skilfully managed to secure economic efficiency.

A representative variety has a specific gravity 1.55, and contains, exclusive of ash, carbon, 94 per cent, hydrogen and oxygen (moisture) 6 per cent. Of the latter, 2½ per cent is hygroscopic, but is held with great tenacity.

The percentage of ash varies greatly, even in the same variety, and in specimens from the same bed. It may be estimated, as an average, at above ten per cent, while the total loss in ash, fine coal, and clinker will be likely sometimes to reach double that proportion in ordinary furnaces. When selecting anthracite it is necessary to keep this fact carefully in mind. Twenty-four samples of anthracite from Pennsylvania, analyzed by Britton, gave as a mean—

Carbon	91.05
Volatile matter	3.45
Moisture	1.34
Ash	4 16
	100.00

There was included in the above, sulphur 0.240, phosphorus 0.013.

A variety of this class of coals, similar in composition, but differing from the typical anthracite above described in structure, has been sometimes called *semi-anthracite*.

It does not exhibit the conchoidal fracture of the latter, but is somewhat lamellar, and is marked by fine joints or planes of cleavage. It crumbles readily, and has less density than the preceding.

One method of distinguishing good examples of the two varieties is found in the fact that the latter, when just fractured, soils the hand, while the former does not. The latter variety kindles quite readily and burns freely.

An example of this coal contained, in one hundred parts, carbon, 90; hydrogen and oxygen, 1.5; ash, 8.5.

65. The Bituminous Coals are sometimes divided into three classes.

Dry bituminous coal contains about 75 per cent of carbon,

5 per cent hydrogen, and 4 per cent oxygen. That part of the hydrogen which is combined with carbon is capable of adding to the heat-giving power of the coal. This coal is lighter than anthracite, its specific gravity being about 1.3. Its color is black or nearly black, and its lustre resinous; it is moderately hard, and burns freely. Its structure is weak, brittle and splintery, fine-grained, and of uneven surface. It kindles with less difficulty than any variety of anthracite, but less readily than the bituminous coal to be described. It burns with a moderate flame, and gives off little or no smoke.

Bituminous caking coal contains sometimes as little as 60 per cent of free carbon, and the maximum proportion is, perhaps, 70 per cent. It contains 5 or 6 per cent each of oxygen and hydrogen, and the remaining portion, amounting sometimes to 30 per cent, is incombustible. Its specific gravity is about 1.25. It is moderately compact; its fracture is uneven, but not splintery; its color is a less decided black than the preceding, and its lustre is more resinous. When heated it breaks into small fragments if the proportion of bitumen is insufficient to cause it to cohere before becoming thoroughly softened, but afterward, as it becomes more highly heated, the pieces become pasty and adherent, and the whole mass becomes compact and hard as the gaseous constituents are expelled by heat.

This coal, ignited in air, burns with a yellowish flame and very irregularly unless kept continually stirred to prevent agglomeration and consequent checking of the draught. It cannot be successfully used, therefore, when great heat is required. It is valuable for the manufacturer of gas and of coke, and can be used in small grates where but moderate heat is obtained.

Long flaming bituminous coal is quite similar to the preceding, differing chemically in composition and containing a larger proportion of oxygen. It burns with a long flame, and has a strong tendency to produce smoke. Some varieties cake like the preceding, others do not; but all ignite readily and burn freely, consuming rapidly.

There are many varieties of coal in each of the above-named classes, the gradation being sometimes marked and sometimes barely distinguishable.

American anthracites have been found, by experiments made under the direction of the United States Navy Department, to have a mean evaporative efficiency, in marine boilers, of 8.9 pounds of water evaporated from 212° Fahr. (100° Cent.) per pound of coal. The bituminous coals of the United States were found to evaporate an average of 9.9 pounds of water per pound of fuel, under similar conditions. The average efficiency of British coals is given by Bourne at about 8.7. American anthracites evaporated 10.69 pounds of water per pound of combustible matter contained in the fuels, and the bituminous coals 10.84, from 212° Fahr.*

These results are practically identical for the two kinds of coal; but the average of the best known varieties gives a difference which is, with such good varieties, in favor of anthracite.

66. **Lignite,** or *Brown Coal,* is of more recent and of more incomplete formation than the bituminous coals, and occupies a position intermediate between the true coals and peat. It contains from 30 to 60 per cent of carbon, 5 to 8 per cent of hydrogen, and 20 to 25 per cent of oxygen. It is very light when pure, having, according to Regnault, a specific gravity of from 1.10 to 1.25. The heavier varieties contain much compact earthy matter.

Lignite is found in tertiary geological formations. It is brown in color, has the woody structure well defined, and is usually lustreless. Where it approaches the bituminous coals in age, it also approximates to them in structure and other characteristics. It frequently contains considerable moisture, which can only be removed by high temperature or by long seasoning, and the lignite, once dried, must be carefully preserved in dry situations if not used at once, as it reabsorbs moisture with great avidity.

When thoroughly dry it kindles readily, burns freely, and is consumed rapidly. It is not usually considered a valuable kind of fuel. It occupies considerably more space weight for weight than the true coals, burns as an average a third more

* See American Institute Reports: Tests of Steam Boilers, 1874.

rapidly, and its evaporation of water per pound of fuel is about 25 per cent less. To obtain maximum evaporative efficiency a slow rate of combustion is found most effective.

67. **Peat,** sometimes called *Turf,* is obtained from bogs and swampy places. It consists of the interlaced and slightly decayed roots of vegetation, which, although buried under a superincumbent mass of similar material and mingled with some earthy matter, retains its ligneous structure and nearly all the chemical characteristics of unaltered vegetable matter. Submitted to the great pressure and the warmth which have for ages acted upon the coal-beds, it would also probably become coal.

Dried in the air, it, like the lignites, retains moisture persistently, and is usually found to contain 30 per cent after drying. After completely removing all water, an average specimen would contain about 60 per cent of carbon, 5 to 10 per cent hydrogen, and 30 or 40 per cent of oxygen. The ash varies very greatly, sometimes being as little as 5, and in other cases as high as 25 per cent.

A pound of wood charcoal has nearly the same value as a fuel as 1.66 pounds of peat of average quality.

Peat is frequently used in large quantities for heating purposes, and attempts have been made, with encouraging results, to use it in metallurgical operations.

When to be thus used, it is cut from the bog with sharp spades, ground up in a machine specially designed for the purpose, and dried by spreading it where it can have full exposure to the sun and air.

It is frequently compressed by machinery until its density approaches that of the lighter coals, and it is used in blocks of such size as are found best suited to the particular purpose for which it is prepared.

Its charcoal makes excellent fuel for use in working steel and welding iron. It is frequently found to be a very excellent fuel for other purposes, and is extensively used in some localities. Its specific gravity is usually about 0.5.

68. **Wood,** thoroughly seasoned, still contains about 20 per cent of moisture.

The moisture being completely driven off by high temperature, there is left about 50 per cent carbon, and combined oxygen and hydrogen compose the remainder, in very nearly the proportions which form water. The pines and firs contain turpentine, and other woods contain frequently a minute proportion of hydrocarbons peculiar to themselves.

The proportion of ash varies from about 0.5 per cent to 5 per cent. The woods all evaporate very nearly the same weight of water per pound of fuel. The lighter woods take fire most readily and burn most rapidly; the denser varieties give the most steady heat and burn longest.

Where radiated heat is desired the hard woods are much the most efficient.

The seasoning of wood is described in that work from which these remarks are abstracted (Materials of Engineering, Vol. I).

Thorough seasoning in the open air requires from six months to a year, and is the only method generally adopted for wood intended to be used as fuel. One cord of hard wood, such as is used on the Northern lakes of the United States, is said to be equal in calorific power to one ton of anthracite coal of medium quality. One cord of soft wood, such as is used by steamers on Western rivers, is equal in heating power to 960 pounds (436 kilogrammes) or 12 bushels (423 cubic decimetres) of Pittsburg coal. One cord of well-seasoned yellow pine is equivalent to ½ ton (500 kilogrammes) of good coal. (See § 84.)

69. **Coke** is made from bituminous coal by subjecting it to such high temperature as to deprive it of its volatile constituents.

The presence of moisture in some of the coals largely reduces their heating power. The bituminous matter causes them to fuse and to form a coherent mass, and, by thus preventing the passage of air, destroys their efficiency for many purposes. The presence of sulphur and of deleterious volatile substances in many coals also precludes their application to the reduction of iron ores, and destroys their value for other metallurgical purposes. All of these volatile materials being driven off by heat, a mass of fixed carbon containing only earthy impurities remains, which "coke" constitutes the fuel with

which some of the most extensive and important metallurgical industries are conducted. These volatile matters are sometimes utilized, but are generally wasted, except where the coke is considered a secondary product, as in the manufacture of illuminating gas.

Coking is carried on by either of three methods—in open heaps, in coke ovens, or in retorts.

The first method is extremely wasteful, and is rarely practised; the second is more economical; and the third is the best where gas is manufactured, and is the only one practised in that case. The second method is that generally adopted where the coke is the primary product, as, although not as economical as the last, it produces a strong coke which is much better adapted for use in furnaces than that afforded by the last method, which, although allowing of the complete separation and collection of the liquid and gaseous products of distillation, yields a coke which has too little density and strength to make it a valuable fuel.

Coak made in ovens is usually of a dark gray color, porous, hard, and brittle. The best gives out a slight ringing sound when struck, and has something of the metallic lustre. It makes an intense, clear fire, and it should not be forced so as to injure either the boiler or the grate by burning the iron. Where the coals contain sulphur but are free from moisture, provision should be made for the pássage of a supply of steam through the oven. This will give up its oxygen to the metal with which the sulphur is combined, and the hydrogen, uniting with the latter, forms sulphuretted hydrogen. The coke is thus left comparatively free from the noxious ingredient, and as this is usually the only constituent of bituminous coal which injuriously affects iron, the coke is a better fuel than the coal from which it is made.

Various coals yield from 33 per cent to 90 per cent of their weight in coke. The latter containing all the ash, the percentage of ash in coke will be higher than in the coal from which it is prepared. Coke has a strong tendency to absorb moisture, and may, when unprotected from dampness, condense 15 or 20 per cent of its own weight within its pores.

Many cokes contain 15 per cent ash and 1 or even 2 per cent sulphur; while others contain but 3 to 5 per cent ash and $\frac{1}{10}$ per cent sulphur.

70. **Charcoal** has the same relation to wood that coke has to bituminous coals.

It is made from all kinds of wood, hard-wood charcoal being the best for fuel. Wood of about twenty years of age is preferred, and should be charred before decay has commenced. The methods of preparation are substantially the same, and the chemical constitution of the product is very similar, although its physical characteristics are quite different.

Charcoal prepared by charring in heaps seldom amounts to more than 20 per cent of the total weight of wood used; carelessness in conducting the process may reduce the weight of product far below even that figure. A considerable loss is unavoidable, since the charring of one portion must be effected by the heat obtained from the combustion of another part of the wood. Sound wood is selected, cut in billets four or five feet in length, and, when large, split into sticks of from three to six inches in thickness. It is best to assort the wood, placing each kind in piles by itself. In making up the heap the ground is cleared, a stake is set at the centre of the cleared space, and a layer of wood is put down with all the sticks laid radially, and the interstices filled with smaller sticks. On this layer the rest of the wood is piled on end, beginning by leaning sticks against the centre stake. The whole is finally covered with another closely packed layer, which in turn is completely covered with sods.

A central hole is left, and also an uncovered ring around the base five or six inches high, for the air-supply. One or two horizontal passages left in the pile conduct the gases to the centre, where they rise, passing out at the hole made by pulling out the centre stake before firing the pile.

The fire being started and actively burning, all openings are closed, and combustion is perfectly controlled by altering their number and position. The condition of the fire is indicated by the color of the smoke, which should be black and thick; when it is light and bluish the draft should be more

completely checked. The work is finished when the wood at the exterior of the pile is found charred. All openings are then closed, and the fire is thus extinguished. The pile can be usually opened on the following day, and the removal of charcoal begun. So crude a process is very liable to excessive losses from the difficulty experienced in adjusting the supply of air, and in conducting the heated products of combustion to precisely the right points, and in precisely the right proportions to secure maximum efficiency.

The presence of moisture in wood is productive of loss by giving rise to the formation of carbonic oxide and of new hydrocarbons. They carry off carbon which would otherwise have been left in the solid state as so much charcoal.

Dry wood, charred in a retort, yields as a maximum about 30 per cent of its weight in charcoal. Of the carbon originally contained in wood, therefore, by the first method of charring not above one half may be expected to be obtained as charcoal, while by the last method three quarters may be obtained by skilful management. The latter process requires the expenditure of about one eighth of the weight of wood charred for the production of the heat demanded by that process. It therefore yields a net amount in charcoal of about 30 per cent of the total weight of wood used. The wood which is used for fuel, however, may be of less value than that charged into the retort. Peat charcoal is sometimes made by similar methods, but is little used.

Wood heated to 300° Fahr. (150° Cent.) for a considerable length of time loses 60 per cent or more of its weight. If heated only to slightly above 212° Fahr. (100 Cent.), the loss is but from 50 to 55 per cent. The residue resembles charcoal, but in each case it retains some volatile matter which may be driven off by higher temperatures. Karsten found that, by rapid charring at high temperatures, he obtained as an average about 15 per cent charcoal in one series of experiments; while by slowly charring the same woods at a low temperature the percentage obtained averaged about 25 per cent.

The combustibility of charcoal is greater when prepared at a low than when prepared at a high temperature.

Good charcoal is black, with a high lustre, and has a conchoidal fracture. It is quite strong, and the best qualities ring when struck, although less than good coke. It burns without flame or smoke, and radiates heat strongly. It should not soil the hands.

Charcoal and coke both make an intense, clear fire, and with a forced draught, giving a small air-supply, afford an extremely high temperature, which is liable to injure the grates or anything metallic which may be subjected to its action.

71. **Pulverized Fuel,** or *Dust-fuel,* is sometimes used in special processes. In the use of this form of fuel special arrangements become necessary to secure thorough intermixture of the fuel with the supporter of combustion, in order to effect complete oxidation. The fuel itself is sometimes prepared by pulverizing coal or other combustibles; and sometimes it is obtained from the large deposits of "slack," "breeze," or coal dust which are found wherever coal in large quantities is subjected to attrition. It is sometimes burned on a very fine grate, the requisite supply of air being secured by the use of a blast beneath the grate.

One of the most successful methods is that pursued by Whelpley and Storer, and by Crampton. In this process a stream of mingled dust-fuel and air is driven into the furnace where combustion takes place, the quantity of fuel and of air being capable of adjustment in such a manner as to secure the most perfect combustion. This method has been applied successfully, not only in the production of heat simply, but also in the reduction of metals from their ores. The facility with which an oxidizing or a reducing flame may be produced at will is the great merit of the process in the latter application. Its advantage for heating purposes lies in the power which it gives of utilizing a fuel which would have otherwise no value. In making "muck-bar," an economy over that attained with coal of above 20 per cent has been reported to have been effected by the use of this process and fuel. The saving occurred in reduction of waste of metal, as well as in simple economy of fuel. At the United States Armory at Springfield, Massachusetts, 6.6 pounds or kilogrammes of fuel were con-

sumed per pound or kilogramme of iron heated to the welding heat, where 16 had been required by the old process.*

72. **Liquid Fuels** have been used to a limited extent. The liquids best adapted for use as fuel are the mineral oils. They yield an intense heat; the products of combustion, as well as the fuels themselves, are comparatively free from deleterious elements, and the temperatures obtained by their use are generally easily regulated, when they are burned in manageable quantities. Their tendency is to give off combustible gases, which may cause serious explosions; and this fact, but especially the difficulty met with in uniformly distributing the oil, and in properly supplying it with air for its combustion, have hitherto prevented the general use of these fuels, even where their comparatively high cost would not be a serious objection to their application.

Crude petroleum, on distillation, breaks up into a large number of hydrocarbon compounds, having boiling-points varying from 32° Fahr. (0° Cent.) to 700° Fahr. (371° Cent.), as given by Van der Weyde. Its density is variable, but usually about 45° Beaumé, corresponding to a specific gravity of about 0.8, the gallon weighing 6.67 pounds, and the litre weighing 0.8 kilogramme. It contains by analysis: carbon, 84; hydrogen, 14; oxygen, 2. The latent heat of its vapor is about one fifth that of steam, and its volume 25 cubic feet to the gallon of oil, or 0.2 cubic metre per litre.

The "creosote" or "dead oil" produced in gas-making is sometimes used as fuel. In experiments on board the British steamer Retriever, in 1868, where creosote was used for the generation of steam by what is called the Dorsett system, the evaporation was about 14 pounds or kilogrammes of water from a boiling-point per pound or kilogramme of liquid fuel used, or nearly double the average obtained where coal was used in the same boiler.

Dr. Paul, reporting these results, gives the theoretic evaporative power of the constituents of this fuel, in units in weight of water per unit of fuel, as follows: phenol, 12.25; cressol,

* Report, Lieut. H. Metcalf to Major Burton, Oct. 31st, 1873.

13.01; napthaline, 15.46; xylol, 16.59; cumol, 16.78; cymol, 16.94.

Capt. Selwyn, R. N., reported an evaporative power from boiling-point of 16.77 parts water per part by weight of a liquid fuel which had a theoretical efficiency of 17.52 parts. In another instance he gives the evaporation of 14.98 from the boiling-point, by a fuel having a theoretical evaporative power of 17.5. Deville found oil from Oil Creek, Pennsylvania, to have a calorific value of 10,000 "calories," equivalent to the evaporation of 16.17 parts of water for one part by weight of oil. Of this 13⅛ per cent was lost by the chimney, and by conduction and radiation. Some other oils give slightly higher figures.

Liquid fuels have probably had most general and successful application in Russia, where Mr. Urquehart and others have adopted it for locomotives, and many steamers in Southern Russia have been fitted with petroleum furnaces. In these cases crude petroleum and refuse is injected into the furnace by means of a steam-jet in which highly-superheated steam is employed. The furnace is lined with fire-brick and the combustion-chamber as well, the burning jets passing first through the latter, then onward to the furnace, where combustion is completed. The brickwork serves as a reservoir of heat, regulating the supply, and also at times re-igniting the jets of oil-spray when they have been for a short time extinguished.

The use of oil on the steamers of the Central Pacific Railway Co. gave in 1884 an economy of from 5 to 12 per cent in total running expense as compared with coal, with great saving of boilers also.

Experiments made by Engineer-in-Chief B. F. Isherwood, U. S. N., under the direction of the U. S. Navy Department, upon various systems of utilization of petroleum as a fuel, gave a maximum economy over the use of anthracite of 68 per cent by Fisher's method of burning oil, and 38 per cent by Foote's process of burning liquid and solid fuel together; he reports the failure of another method, in consequence of the obstruction of the tubes by deposition of solid carbon.

Isherwood states the advantages attending the use of the

mineral oils, which were the subject of his experiments, as follows:

1. A reduction of weight of fuel amounting to 40½ per cent.

2. A reduction in bulk of 36½ per cent.

3. A reduction in the number of firemen ("stokers") in the proportion of 4 to 1.

4. Prompt kindling of fires, and consequently the early attainment of the maximum temperature of furnaces.

5. The fire can at any moment be instantaneously extinguished.

Other advantages, unmentioned by him, are the uniformity of combustion and heating attainable, and the small proportion of ash. The disadvantages are given as follows:

1. Danger of explosions occurring by the taking fire of the vapors which are liable to arise from the fuel, and to escape from the tanks.

2. Loss of fuel by evaporation.

3. The unpleasant odors which distinguish these vapors.

4. The comparatively high price, which price would be rapidly augmented by any general introduction of the proposed application of the oils.*

73. **Gaseous Fuels** are used with marked success in some branches of metallurgical work, as well as in the generation of heat for ordinary purposes.

The advantages possessed by gaseous fuels are:

1. Convenience of management of temperature.

2. Freedom from liability to injure material with which the products of combustion may come in contact, and consequently, also, allowing the use of fuel of inferior quality as a source of the gas.

3. The facility with which thorough combustion may be secured.

4. The readiness with which the flame may be given either an oxidizing or a deoxidizing character.

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* This may be questioned, since recent explorations of oil deposits, especially of the United States, indicate an immense supply. (See discussion by Dr. Dudley, J. F. Inst., 1888.)

5. In many cases economy in expense of operation.

The disadvantages are:

1. Danger of explosions when carelessly or unskilfully handled.

2. Expense of plant.

74. **Artificial Fuels**, other than charcoal, coke, and gases, are occasionally used in the production of high temperatures.

They are prepared principally from refuse of natural fuels, which has but little value in its usual condition, but which, by special processes, is simply mixed with a small proportion of fuel of better quality or of more manageable form, and is compressed by machinery into conveniently shaped blocks, called *briquettes*. This refuse is found in large quantities in the neighborhood of coal-mines, and wherever coal is handled in considerable quantities.

The total loss in this form in mining and transportation amounts to from one third to one half. It is called, as has been before stated, *slack-coal*.

In the manufacture and transportation of coke and of charcoal, large quantities of refuse, called "breeze," accumulate; which, although very rich in combustible matter, cannot be utilized in the condition in which it is found, except by special contrivances. The sawdust which accumulates about saw-mills is another variety of combustible belonging to the same class; as is also spent tan-bark, from tanneries, and "bagasse," or refuse crushed sugar-cane.

They are most frequently mixed with some cohesive and at the same time combustible substance, as coal-tar. In districts abounding in mineral hydrocarbons, as in the neighborhood of the Caspian Sea, it has long been customary to mix them with clay, and thus to form a coherent and manageable fuel. The Norwegians have also long practised their method of utilizing sawdust by mixing it with clay and vegetable tar, and moulding it into bricks of such size and shape as to be conveniently handled, and at the same time to burn freely and without waste. It has been often urged, and with some reason apparently, that for many purposes a fuel made by careful mixture of dust-fuel with pitch or other combustible

cementing material is preferable to ordinary coal, in consequence of the greater convenience with which it can be stowed and handled.

Another method of utilizing waste fuels consists in thoroughly mixing, by grinding, charcoal-dust from the kilns with charred peat, spent tan-bark, and the proper proportion of tar or pitch to make a pasty, adhesive mass. This is moulded by machinery and dried in the open air, and then finally baked in closed retorts at a low heat. Dust-coal and pitch have been made into a good fuel in quite a similar manner to that just described.

75. **The Heating Power of any Fuel** is determined by calculating its *total heat of combustion*. This quantity is the sum of the amounts of heat generated by the combustion of the unoxidized carbon and hydrogen contained in the fuel, less the heat required in the evaporation and volatilization of constituents which become gaseous at the temperature resulting from the combustion of the first-named elements. It is measured in "thermal units."

A *thermal unit* is the quantity of heat necessary to raise a unit weight of water, at temperature of maximum density, one degree of temperature. The British thermal unit is the quantity of heat required to raise a pound of water from the temperature 39°.1 to 40°.1 Fahr. The metric unit or calorie is the quantity of heat required to raise one kilogramme of water (2.2046215 pounds) from 3°.94 to 4°.94 Centigrade.

One metric or centigrade unit is equal to 3.96832 British units, and a British unit is equal to 0.251996 metric unit.

An approximate estimate of the number of thermal units developed by the combustion of a pound or kilogramme of any dry fuel, of which the chemical composition is known, may be obtained by the use of the following formula:

$$\left.\begin{aligned} h &= 14{,}500C + 62{,}000\left(H - \frac{O}{8}\right), \\ h' &= 8{,}080C + 34{,}462\left(H - \frac{O}{8}\right), \end{aligned}\right\} \quad . \quad . \quad . \quad (1)$$

where h is the number of British thermal units representing the total heat of combustion of one pound of the fuel; h' is the number of metric units per kilogramme of fuel; C represents the percentage of carbon, H that of hydrogen, and O that of oxygen.

Thus an anthracite coal has been found to have the following composition:

COMPOSITION OF ANTHRACITE COAL.

	Per cent.
Carbon	81.34
Hydrogen, *uncombined*	3.45
Hydrogen, *in combination*	0.74
Oxygen and Nitrogen	5.89
Sulphur	0.64
Water	2.00
Ash	5.94
Total	100.00

One pound or kilogramme of coal, of which the above is an analysis, can evaporate theoretically 14.4 pounds or kilogrammes of water from and at 100° Centigrade, or 212° Fahr.

M. M. Scheurer, Kestner, and Meunier have adopted the common formula as first proposed by Dulong, but would omit all account of oxygen, thus reducing, as is claimed, the average error of the formula from about 12 per cent or more to 8 or 10. M. Cornut would separate the fixed from the volatile carbon, and would give the latter about one third more credit for heating power than the former; closer approximations are thus made than by the other methods.

Various methods of approximate determination of the heating power of fuels have been proposed. The use of the calorimeter is probably the most satisfactory; another method is that of computation from the known chemical composition of the fuel, and the law of Walter, who found the quantity of heat produced in combustion very closely proportional to the weight of oxygen absorbed. Berthier's method is often employed: this consists in heating the fuel sample to a red heat, in a closed vessel, with litharge or other source of oxygen. When lead oxide is thus used, the weight of lead reduced to

the metallic state is a measure of the oxygen absorbed. The method is simple and easy of practice, but is not sufficiently accurate to be generally approved.

The value of h or of h' ranges between 5500 British or 1386 metric units for dry wood, and 16,000 or 4032 for the best known coals. The equation given is deduced from the experiments of MM. Favre and Silbermann, who determined the total heat of combustion of one pound of pure carbon to be 14,500 British or 3654 metric thermal units, and of one pound of hydrogen to be 62,000 British units, or 15,624 calories. The combustion of one kilogramme of each would develop 31,967 British or 8080 metric units, and 136,686 British or 34,462 metric units, respectively.

The combustion of the several kinds of carbon produces the development per unit of weight of:

British Units.	Metric Units.	Material.
13,986	7,770	Diamond.
13,968	7,760	Iron Graphite.
14,040	7,800	Natural Graphite.
14,490	8,050	Gas Carbon.
14,500	8,080	Wood Charcoal.

Where the chemical composition of the fuel is unknown and cannot be readily ascertained, its heating effect may be determined experimentally by burning a known weight and passing the products of combustion through a calorimeter of such area of heating-surface as to reduce their temperature very nearly to that of the atmosphere before discharging them.

The table given hereafter exhibits the total heating effect of various fuels as estimated from analyses of good specimens.

Where the heat produced is not so thoroughly utilized as to cause the condensation of vapors which may pass off with the permanent gases resulting from combustion, there is necessarily a greater loss of the heat of combustion of hydrogen than of that of carbon, and the relative heating efficiency of carbon is considerably increased by the facts that it must be raised to red heat as a solid before combustion can occur, and that the specific heat of carbonic acid (0.216) is only about one half that of aqueous vapor (0.475).

The general formulas, as given by Watts, for ascertaining the thermal effect of any fuel of a known composition are as follows:

For combustion in oxygen:

$$T = \frac{cC + c'H - lW}{s.3.67C + 9H + s'W} \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (2)$$

For combustion in air:

$$T = \frac{cC + c'H - lW}{s.3.67C + 9H + s'W + s''N + s'''A} \quad . \quad . \quad (3)$$

Here $T =$ increase of temperature produced by combustion;
C and $H =$ quantities of carbon and hydrogen available in 1 part by weight of the fuel;
$W =$ total quantity of water yielded by 1 part by weight of the fuel;
$l =$ latent heat of water;
$s, s', s'', s''' =$ specific heat of carbonic acid, water-vapor, nitrogen, and air;
c and $c' =$ calorific power of carbon and hydrogen;
$N =$ quantity of nitrogen in air necessary for converting combustible constituents of 1 part by weight of fuel into carbonic acid and water;
$A =$ extra quantity of air supplied for combustion.

76. **The Temperature of the Fire** depends, not solely on the amount of heat generated by combustion, but also on the quantity and nature of the resulting products of combustion.

The total heat generated by the combustion of fuel is all communicated to the products of combustion, which are usually gaseous, giving them a temperature which is determined, partly by the calorific power of the fuel, and partly by their nature. Thus, carbon requires for its combustion to carbonic

acid 2.67 times its weight of oxygen, producing 3.67 times its weight of carbonic acid.

The heat generated by combustion of carbon is capable of raising 8080 times its weight of water from 4° to 5° C., and would raise the temperature of water equal in weight to the carbonic acid produced, about 2202° C.*—i.e., $8080 \times 1° = 2201°.63 \times 3.67$.

But the specific heat, or capacity for heat, of water is greater than that of carbonic acid; the increase of temperature in the carbonic acid produced is correspondingly greater than the rise in temperature that would be produced in a quantity of water equal to 3.67 times the weight of carbon burnt. The quantities of heat necessary to produce equal increase of temperature in equal weights of carbonic acid and of water being in the proportion of 0.2164 : 1.0000, the amount of heat needed to raise the temperature of 3.67 parts water and 3.67 parts carbonic acid one degree, are as

$$\frac{3.67}{3.67 \times 0.2164} = \frac{3.67}{0.794}.$$

Hence the rise in temperature of the 3.67 parts of carbonic acid, to which the heat of combustion of 1 part carbon is transferred, may be calculated by dividing the given number of heat-units by the amount of heat required to raise the temperature of the 3.67 parts carbonic acid one degree, or

$$\frac{8080}{0.794} = 10{,}174° \text{ C.} = 18{,}345° \text{ F.}$$

The heat of combustion of hydrogen is sufficient to raise the temperature of 34,462 times its weight of water 4° to 5° Cent., but it requires for its combustion 8 times its weight of oxygen, and produces 9 times its weight of vapor. The prod-

* Watts' Dictionary of Chemistry.

ucts of combustion weigh nearly $2\frac{1}{4}$ times as much as those of the combustion of an equal weight of carbon. Some of the heat produced by the combustion of hydrogen becomes latent and does not increase the temperature of the gases.

The latent heat of water, or that needed to convert 1 part of water at 100° C. into steam, is 537 times as much as is needed to raise the temperature of an equal weight of water from 4° to 5° C., and 966.1 times the quantity which will raise the temperature of one part from 39°.1 to 40°.1 Fahrenheit. The quantity of heat latent in the 9 parts vapor produced by the combustion of hydrogen will therefore be 4833 metric heat-units; this must be taken from the total amount of heat generated in calculating the quantity of heat producing rise in temperature.

	Parts by weight of water vapor.	Metric Heat-units.		British Heat-units.
Total heat of combustion of 1 part hydrogen....................		34,462		62,000.0
Latent heat of water in heat-units..	$9 \times 537 =$	4,833	$9 \times 966.1 =$	8,694.9
Available heat....................		29,629	=	53,305.1

The specific heat of water vapor is 0.475; the heat raising the temperature of 9 parts water and 9 parts water vapor have the proportion

$$\frac{9 \times 1}{9 \times 0.475} = \frac{9}{4.275},$$

and the rise in temperature will be

$$\frac{29629}{4.275} = 6930°.7 \text{ C.} = 12,475°.3 \text{ F.}$$

Thus the heating and the calorific power are not necessarily the same. The heating effect depends only partly upon the calorific power of the fuel burnt.

RECAPITULATION. (WATTS.)

	Weight.	Weight of Oxygen.	Ratio.	Weight of Products.	Ratio.	Heat-units.	Ratio.	Thermal Effect.	Ratio.
Carbon....	1	2.67	1	3.67	1	8080	1.000	10176°	1.000
Hydrogen..	1	8	3	9.00	2.4	34,462	4.265	6930.7°	0.681

In these examples combustion takes place in oxygen, and with no more than is theoretically needed. In all actual cases of combustion, atmospheric air supplies the oxygen supporting the combustion. Nitrogen, of which it contains 77 per cent, dilutes the products of combustion and reduces the temperature. In the case of combustion of carbon in air, the nitrogen in air containing 2.67 parts of oxygen amounts to 8.94 by weight.

The specific heat of nitrogen is 0.244, and the quantity of heat needed to raise the temperature of the nitrogen from 4° to 5° C. is:

$$8.94 \times 0.244 = 2.181 \text{ units.}$$

Adding to this the heat needed to raise the temperature of the carbonic acid produced, the amount of heat needed to raise the temperature of all the products of combustion in air from 4° to 5° C. will be

$$2.181 + 0.794 = 2.975 \text{ units.}$$

And the elevation of temperature will be

$$\frac{8080}{2.975} = 2715^\circ \text{ C.} = 4887^\circ \text{ F.}$$

Burning hydrogen in air, the nitrogen in air containing 8 parts of oxygen is, by weight, 26.78 parts, and the amount of heat needed to raise its temperature from 4° to 5° C. is:

$$26.78 \times 0.244 = 6.534 \text{ units,}$$

and the consequent rise in temperature will be

$$\frac{29629}{4.275 + 6.534} = 2741° \text{ C.} = 4934° \text{ F.}$$

The difference between the temperatures attainable by the combustion of carbon and hydrogen in oxygen and in air is much the greatest with carbon, as the quantity of heat produced by its combustion is much less than that generated by burning hydrogen, thus:

RECAPITULATION. (WATTS.)

	Calorific Power.	Ratio.	Temperature Produced. In Oxygen.	Ratio.	In Air.	Ratio.	Difference.	Ratio.
Carbon..........	8.080	1.000	10,174°	1.000	2,715°	1.002	7,459	1.000
Hydrogen.......	34.460	4.265	6,930°	0.681	2,741°	1.009	4,189	0.561

Thus in all cases where high temperatures are demanded, it is of advantage to increase the amount of oxygen in the air supporting combustion, and to restrict the influx of nitrogen and of superfluous air. Thus also the reason of the attainment of high temperatures by combustion in pure oxygen with the oxyhydrogen blow-pipe is readily seen.

The quantity of air supplied is usually much greater than that simply required to furnish the oxygen to consume the combustible. In practice it often amounts to twice as much, and is rarely less than one and a quarter times the quantity theoretically needed, and there consequently follows a proportionate reduction of the temperature attainable. When carbon is burnt with twice as much air as is theoretically needed, the products of combustion have 24.22 times the weight of the carbon, and with hydrogen 80.56 times the weight of the hydrogen.

AIR REQUIRED TO SUPPLY A DOUBLE AMOUNT OF OXYGEN.

	Parts by Weight of Air.	Volume of Air at 60° F. per Lb. of Fuel, Cubic Feet.	Parts by Weight of Gaseous Products.
Carbon............ 1..	23.22	303.39	25.22
Hydrogen.......... 1..	79.56	908.62	80.56

The specific heat of air is 0.2377, and the quantities of heat needed to raise the temperature of the air demanded from 4° to 5°, and the temperature resulting from combustion are:

Combustion of carbon:

$$2.7597 = 11.61 \times 0.2377,$$

and $$\frac{8080}{2.759 + 2.975} = 1408° \text{ C.}$$

Combustion of hydrogen:

$$34.78 \times 0.2377 = 8.2672,$$

and $$\frac{29,629}{8.2672 + 10.8093} = 1553° \text{ C.}$$

It is evidently always desirable to secure perfect combustion, and with the least possible air-supply. With the forced draught produced by a fan or blast-pipe, fuel may be burnt with less air than with a chimney draught, and can be utilized with greater economy of heat. This economy is greater with fuel containing but little volatilizable matter.

Dissociation is a phenomenon which probably rarely if ever occurs in familiar practice. Oxygen and hydrogen, combined to form water, or steam, at ordinary furnace temperatures, are separated again by heat-energy when the temperature is somewhere below 6000° Cent. (10,832° Fahr.). St. Claire Deville, the first to observe and study this phenomenon, concluded that dis-

sociation may commence at 1000° Cent. (1832° Fahr.) or below that heat.* Deville and Debray reported the temperature of the common oxyhydrogen flame to be not above 2500° Cent. (4532° Fahr.), and Bunsen found that under increasing pressures the temperature limit as fixed by dissociation was raised until, at ten atmospheres, it had increased ten per cent or more.

77. **The Minimum Quantity of Air** required for the perfect combustion of any kind of fuel may be readily calculated from its known chemical constitution.

Calling the weight of air W, and denoting the weights of carbon, hydrogen, and oxygen, C, H, and O,

$$W = 12C + 36\left(H - \frac{O}{8}\right). \quad . \quad . \quad . \quad . \quad . \quad (4)$$

The value of W ranges from 6 for dry wood, to 12 for anthracite and good bituminous coal. Charcoal and the softer bituminous coals require about 11 parts by weight of air per 1 part of fuel.

These values can only be approximated, in practice, with extremely slow and carefully managed combustion. A perfect intermixture of the combustible with the supporter of combustion can only be secured by the admission of some excess of air to the furnace. Probably about double the estimated amount of air is usually provided, although in some cases, where a forced draught produces exceptionally complete intermixture of the gases, the quantity may be brought as low as 18 pounds of air per pound of coal.

In one instance, in which a furnace burning wet fuel was tested by the Author, to determine its economic efficiency, the quantity of air supplied was very little in excess of that dictated by theory. This was, however, an exceptional case. As the excess of air must be heated to the temperature of the chimney, and then thrown away, it causes a notable waste of heat.

The weight of a cubic foot of air at mean atmospheric temperature being 0.076361 pound, the *volume* of air required for

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* Archives des Sciences Physiques, 1860, t. ix., p. 51.

perfect combustion, in any case, may be determined by the equation:

$$V = 157C + 471\left(H - \frac{O}{8}\right). \quad . \quad . \quad . \quad . \quad (5)$$

Eighteen and twenty-four pounds of air, required, as stated above for combustion, in the case mentioned, of one pound of coal, would measure, respectively, 236 and 314 cubic feet.

The weight of a cubic metre of air is 1.224 kilogrammes. The volume, in metric measures, required in any case is therefore

$$V' = 9.8C + 29\left(H - \frac{O}{8}\right). \quad . \quad . \quad . \quad . \quad (6)$$

When eighteen and twenty-four times the weight of fuel are required respectively, the volumes in the case taken would be 15 and 19 cubic metres.

78. The Temperature of the Products of Combustion may be calculated, as has been shown, with approximation to accuracy, from the known weight of the fuel and of the products of combustion, the heat-generating power of the former, and the specific heat of the latter.

The specific heat of the products of combustion are, at constant pressure, and for equal weights:

SPECIFIC HEATS OF PRODUCTS OF COMBUSTION. (REGNAULT.)

(*Water* = 1. *Pressure constant.*)

Air	0.2374
Oxygen	0.2175
Nitrogen	0.2438
Steam	0.4805
Carbonic acid	0.2164

The proportions in which these substances occur in the products of combustion being known, the mean specific heat of all may be determined; and the total heat of combustion of one pound of fuel being divided by the product of this weight by

this mean specific heat, the quotient is the probable temperature of the furnace gases.

Rankine gives the result of this calculation, in cases where carbon alone is burned with undiluted air, and diluted with one half and with equal weight of additional air, respectively, 4580°, 3215°, and 2440° Fahr., equal to 2627°, 1824°, and 1338° Cent.

Olefiant gas, similarly treated, should give temperatures of 5050°, 3515°, and 2710° Fahr.; or 2788°, 1953°, and 1488° Cent

The mean specific heat of the products of combustion is practically equal to the specific heat of air.

The following are the specific heats given by Rankine:

SPECIFIC HEAT UNDER CONSTANT PRESSURE.

Carbonic-acid gas	0.217
Steam	0.475
Nitrogen, probably	0.245
Air	0.238
Ashes	0.200

Durham (British) coke, having the composition (Deering) of—

Carbon	93.78
Sulphur	0.82
Ash	5.40
Total	100.00

liberates 13,640 British thermal units per pound and requires 10.91 pounds of air per pound of fuel, for complete combustion, the heat produced being 1145 units per pound, the resultant rise in temperature being 4877° F. (2709° C.), and the amount of water evaporated, as a maximum, being 14.12 times the weight of the coke.

The best bituminous coal contains, as an example,

Carbon	81.47
Hydrogen	4.97
Nitrogen	1.63
Oxygen	5.32
Sulphur	1.10
Ash	5.51
Total	100 00

Its complete combustion requires 10.99 times its weight of air, giving a rise of temperature of 4830° F. (2683° C.) and an evaporation of 14.64 times its weight of water from and at the boiling-point. The heat produced is 14,143 units per pound of fuel, or 118° per pound of furnace gases.

Oak wood, according to Deering,* has the composition, when kiln-dried,

Oxygen	41.27
Hydrogen	6.00
Nitrogen	1.13
Carbon	49.95
Ash	1.65
Total	100.00

It will evaporate 7.98 times its own weight of water, developing 7713 British heat-units per pound, demanding 6.08 times its own weight of air for complete combustion, the products of combustion containing 1089 heat-units per pound and attaining a temperature of 4287° F. (2382° C.).

Pennsylvania petroleum, having the composition, according to Deering, of

Carbon	85	Hydrogen	15

requires 15 times its own weight of air for complete combustion, liberates 20,360 British thermal units per pound of the liquid, or 1267 per pound of products of combustion, and develops an increase of temperature of 4900° F. (2722° C.).

Illuminating gas, according to Mr. Deering, having the composition,

Carbon	61.26
Hydrogen	25.55
Nitrogen	8.72
Oxygen	4.47
Total	100.00

develops 20,801 British thermal units per pound, equivalent to

* Howard Lecture. W. Anderson. London, 1885.

the evaporation of 21.53 times its own weight of water, the best mixture for complete combustion being 15.66 parts of air, by weight, to one of the gas. The rise in temperature with perfect combustion is 4567° F. (2537° C.), the total heat liberated being 1250 British thermal units per pound of the mixture.

The same gas, per 1000 cubic feet, weighs as follows:

Carbon	18.19 lbs.
Hydrogen	7.58 "
Nitrogen	2.59 "
Oxygen	1.33 "
Total	29.69 lbs.

It produces 617,485 units of heat, and can evaporate 639 pounds of water, demanding 465 pounds of air for complete combustion.

By using the data of Rankine, results are obtained for the two extreme cases of *pure carbon* and *olefiant gas*, burned respectively in air; British units are used thus:

	Carbon.	Olefiant Gas.
Total heat of combustion per pound	14,500	21,300
Weight of products of combustion in air, undiluted	13 lbs.	16.43 lbs.
Their mean specific heat	0.237	0.257
Specific heat × weight	3.08	4.22
Elevation of temperature, if undiluted	4,580°	5,050°

If diluted with air = ½ air for combustion.

Weight per lb. of fuel	19.	24.2
Mean specific heat	0.237	0.25
Specific heat × weight	4.51	6.06
Elevation of temperature	3,215°	3,515°

If diluted with air = air for combustion.

Weight per lb. fuel	25.	31.86
Mean specific heat	0.238	0.248
Specific heat × weight	5.94	7.9
Elevation of temperature	2,440°	2,710°

For wet fuel, like sawdust, or spent tan from the leach, the Author has made the following estimation in one actual case

where the fuel consists of 45 per cent of woody fibre, and 55 per cent of water.

Taking the available heat per pound of the dry portion at 6480 British thermal units, each pound of wet fuel yields 2916 units of heat. Of this, 531.6 are absorbed in the evaporation of the 55 per cent of water, leaving 2384.4 units to raise the temperature of the products of combustion. Of these there are, as a minimum, 3.7 pounds, having a mean specific heat of about 0.287.

The elevation of temperature is therefore 2245.3° Fahr., and adding the mean temperature of the atmosphere, 74°, the mean temperature of furnace, assuming no dilution with unused air, and no losses, would have been about 2320° Fahr. (1271° Cent.). Losing $2\frac{1}{2}$ per cent by radiation and conduction, etc., the actual temperature was 2260° Fahr. (1238° Cent.).

The temperature of chimney flue was found by experiment to have been 544°. The furnace gases were therefore cooled $2260° - 544° = 1716°$ Fahr. (937° Cent.) by the loss of the heat given up to the boiler. This is equivalent to $1716 \times 0.287 = 492.5$ British heat-units per pound of gas, and to 4049.4 units per pound of ligneous material in the fuel.

The "equivalent evaporation," from and at 212°, is $4049.4 \div 966.6 = 4.18$ pounds of water. The actual evaporation was equivalent to 4.24 pounds, and the difference—less than one per cent of the total—represents losses and errors of calculation.

The actual existing temperature of furnace can be also thus estimated. The available heat per pound of fuel, including water, has been given at 2916 British thermal units. Of this $\frac{531.6}{2916} \doteq 0.182$ passed off with vapor, and was not useful in raising the temperature of either the furnace or the chimney. Hence, of all heat liberated, $1.00 - 0.182 = 0.818$ was efficient in elevating the temperature of furnace, and $0.37 - 0.182 = 0.188$ was effective in producing the observed temperature, 544° Fahr., of chimney. Then, since the same quantity of gas passes at both places, the temperature of furnace was $\left(\frac{0.818}{0.188} \times 470\right) + 74° = 2119°$ Fahr. To this is to be added

the slight loss of temperature *en route* between furnace and chimney by conduction and radiation, which may make the figure very nearly 2260° Fahr., as above.

The actual temperature of the furnace may be judged, in any case, by observing the brilliancy of the light radiated from any solid in its midst, and presumably at its own temperature, as by the following table given by Pouillet:

Appearance.	Temp. Fahr.
Red, just visible	977°
" dull	1290
" cherry, dull	1470
" " full	1650
" " clear	1830
Orange, deep	2010
" clear	2190
White heat	2370
" bright	2550
" dazzling	2730

To determine temperature by fusion of solids, we have also from the same authority—

Substance.	Temp. Fahr.
Tallow	92°
Spermaceti	120
Wax, white	154
Sulphur	239
Tin	455
Metal.	
Bismuth	518
Lead	630
Zinc	793
Antimony	810
Brass	1650
Silver, pure	1830
Gold coin	2156
Iron, cast, medium	2010
Steel	2550
Wrought-iron	2910

79. **The Rate of Combustion** is determined principally by the quantity of air supplied. The amount of coal burned per square foot of grate with chimney draught varies very

nearly with the square root of the height of the chimney, and has been found by the Author, ordinarily, to be very nearly, as a maximum,

$$W = 2\sqrt{H} - 1, \quad \text{or} \quad W' = 17\sqrt{H'} - 0.5,$$

where W and W' are weights of fuel burned per hour per square foot of grate, and on the square metre, in pounds and kilogrammes, and H and H' are the heights of chimney in feet and metres.

A chimney 64 feet or 19½ metres high, will, for example, under favorable conditions, usually support combustion of 15 pounds of coal per square foot of grate, or of 73 kilogrammes per square metre. The weight of combustible which may be burned in any unit of time may be calculated approximately by dividing the weight of air which can be supplied in that time, by its proportion to weight of fuel, as determined in the preceding paragraphs. In exceptional cases there is sometimes a large excess of air, and sometimes a considerable deficiency. In such instances, direct experiment only can determine the amount of fuel burned.

80. The Efficiency of the Furnace, considered as a heat-utilizing apparatus, is determined by the temperature of furnace gases, by the thoroughness with which complete combustion is secured, and with which losses of fuel and of heat are prevented. It is measured by the ratio of the amount of the total available heat of the fuel to that of the heat actually utilized. This efficiency is rarely so high as 80 per cent, and frequently falls to 50 per cent.

In all cases, efficiency is to be studied, in applications of heat, in two parts: (1) the efficiency of the heat-generating and absorbing apparatus, i.e., the furnace; (2) the efficiency of the heat-utilizing apparatus and methods, as the steam-boiler, the heating-chamber of the reverberatory furnace, or such other heat-absorbing arrangement as may be adopted.

(1) The efficiency of the furnace is represented by

$$E = \frac{T_1 - T_2}{T_1 - T_3},$$

in which E is the ratio of the heat rendered available to heat developed; T_1, T_2, T_3, are the temperatures of furnace, of chimney, and of external air. For examples, in two actual cases, T_1, T_2, T_3, were, 2118° F., 544° F., and 74° F., or 1176°, 302°, or 510°, 251°, and 48° C. for the second case. The values of the efficiencies of the two kinds of apparatus were

$$\frac{2118^\circ - 544^\circ}{2118^\circ - 74^\circ} = 0.77; \quad \text{and} \quad \frac{919^\circ - 452^\circ}{919^\circ - 86.5^\circ} = 0.56;$$

or for Centigrade degrees,

$$\frac{1176^\circ - 302^\circ}{1176^\circ - 41^\circ} = 0.77; \quad \text{and} \quad \frac{510^\circ - 251^\circ}{510^\circ - 48^\circ} = 0.56;$$

the first being nearly 40 per cent higher than the second. A certain change of fuel would have given the first a maximum temperature of 2644° F., 1451° C., and would have raised its efficiency to

$$\frac{2644^\circ - 544^\circ}{2644^\circ - 74^\circ} = 0.81,$$

or

$$\frac{1451^\circ - 279^\circ}{1451^\circ - 23^\circ} = 0.81.$$

(2) The efficiency of the heat-absorbing apparatus is dependent upon the character and proportion, and is not treated here. The highest efficiency in heat-production is secured by perfect combustion with the least practicable air-supply, thus obtaining the highest possible resulting temperature.

A large part of the heat produced by combustion of fuel is expended in procuring chimney draught. This is not available for producing any other useful effects.

The amount of heat thus expended varies with the nature of the products of combustion, and the use to which the heat

is to be applied. In all cases the heat thus discharged is wasted.

The temperature of the products of combustion cannot usually be reduced much below about 600° F., or 315° C.

81. Economy in Combustion of Fuels, where they are used simply in the production of high temperature, is so important a matter, except in those favored localities where the proximity of coal, or of peat-beds, or of forests, renders its waste less objectionable, that the engineer should omit no precaution in the endeavor to secure their perfect utilization.

To secure the greatest economy, it is necessary to adopt a form of grate which, while allowing a sufficient supply of air to pass through it to insure complete combustion, has such narrow air-spaces as to prevent waste of small fragments, by falling through them.

The narrower the grate-bars and the air-spaces, the more readily can losses from this cause and from obstruction of draught be avoided. With a hot fire, however, the difficulties arising from the warping of the bars become so great, that it is only by peculiar devices for interlocking and bracing them that their thickness can be reduced below about $\frac{7}{8}$ of an inch at the top. Many such devices are now in use. In furnaces burning wet fuel, with an ash-pit fire, fire-brick grate-bars are used.

A certain amount of air must usually be allowed to enter the furnace above the grate, to consume those combustible gases which do not obtain the requisite supply of oxygen from below. The carbon, probably, in such cases usually obtains its oxygen from below the grate, while the gaseous constituents of the fuel are consumed by the oxygen coming in above.

Chas. Wye Williams, who made most extended and careful experiments on combustion of fuel, recommended, for ordinary cases, where bituminous coal was burned, a cross area of passage, admitting air above the grate, of one square inch for each 900 pounds of coal burned per hour, or about one square centimetre for each 63 kilogrammes of fuel. This area should be made larger, proportionally, as the thickness of the

bed of the fuel is increased, and as the proportion of hydrocarbons becomes greater.

Chilling the gases, before combustion is complete, should be carefully prevented; and comparatively cold surfaces, as those of a steam-boiler, should not be placed too near the burning fuel. A large combustion-chamber should, where possible, be provided, and more complete combustion may be expected in furnaces of large size, lined with fire-brick, and with arches of the same material, than in a furnace of small size where the fire is surrounded by chilling surfaces, as in a "fire-box steam-boiler."

Finally, the greatest possible amount of heat being developed in combustion, careful provision should be made for completely utilizing that heat.

In a steam-boiler this is accomplished by having large heating-surfaces, and by so arranging the distribution of the adjacent currents of water and of hot gases that their difference of temperature shall be the greatest possible. The gases should enter the flues at that part of the boiler where the temperature is highest, and leave them at the point of lowest temperature. The feed-water should enter as near as possible to the point where the gases pass off to the chimney, and should gradually circulate until evaporation is completed at, as nearly as possible, that part of the boiler nearest to the point of entrance of the heated gases.

Where a small combustion-chamber is unavoidably employed, as in locomotives, various expedients have been devised with the object of producing complete intermixture of gases before entering the tubes. The most common and most successful is a bridge-wall, sometimes depending from the crown sheet, but sometimes rising from the grate, and which, by the production of eddies in the passing current, causes a more thorough commingling of the combustible gases with the accompanying air. None of these devices seem yet to have given such good results as to induce their general adoption.

In the furnaces of steam-boilers it is usually considered advisable to allow the gaseous products of combustion to enter the chimney at a temperature of about 600° Fahr. (315° Cent.),

or about 2.08 times the absolute temperature of the external air, where natural draught is employed. Rankine has stated that the best temperature of chimney for natural draught is that at which the gases have a density equal to about one half that of the external air. Thus, the temperature of the external air being 60° Fahr. (15°.5 Cent.), its absolute temperature is 521°.2 (261°.75 Cent.), and the required absolute temperature of the gases in the chimney will be this temperature multiplied by $2\frac{1}{12}$, i.e., $521°.2 \times 2\frac{1}{12} = 1085°.8$, and the corresponding temperature on the ordinary scale is 624°.6 Fahr. (339°.2 Cent.).

With forced draught, a considerable economy may be effected by the reduction of the temperature of escaping gases approximately to that of the boiler itself at the point of discharge of the gases.

The fuel should be usually burned at a fair rate of combustion, and in such manner as to give that degree of efficiency which has been found financially desirable. The air-supply should be provided for, partly above as well as below the grates, bituminous coal demanding more above the bed of fuel than anthracite, partly because it is needed to burn the gaseous hydrocarbons driven off from the former, and partly because the bituminous fuel is burned in a thicker and less permeable bed of fuel. Ten or fifteen per cent of the total air-supply should usually be furnished above the flame-bed.

The grate-area should always be so proportioned that it shall be possible to keep it, in ordinary working, at all times well and uniformly covered with incandescent fuel. The space above the grate, between it and the heating-surfaces, should always be so large that ample space and time are given for thorough intermixture of gases and complete combustion, and it should have such form that the air introduced above the fuel may become well mingled with the gases distilled from the coal. The effect of this air-supply, where bituminous coal is used, is well shown in an experiment by Mr. Houldsworth,* made in 1842 for the British Association, at its Man-

* Fuel Combustion and Economy; C. W. Williams. "On the Consumption of Fuel, etc.;" Wm. Fairbairn, Trans. Brit. Assoc. 1842.

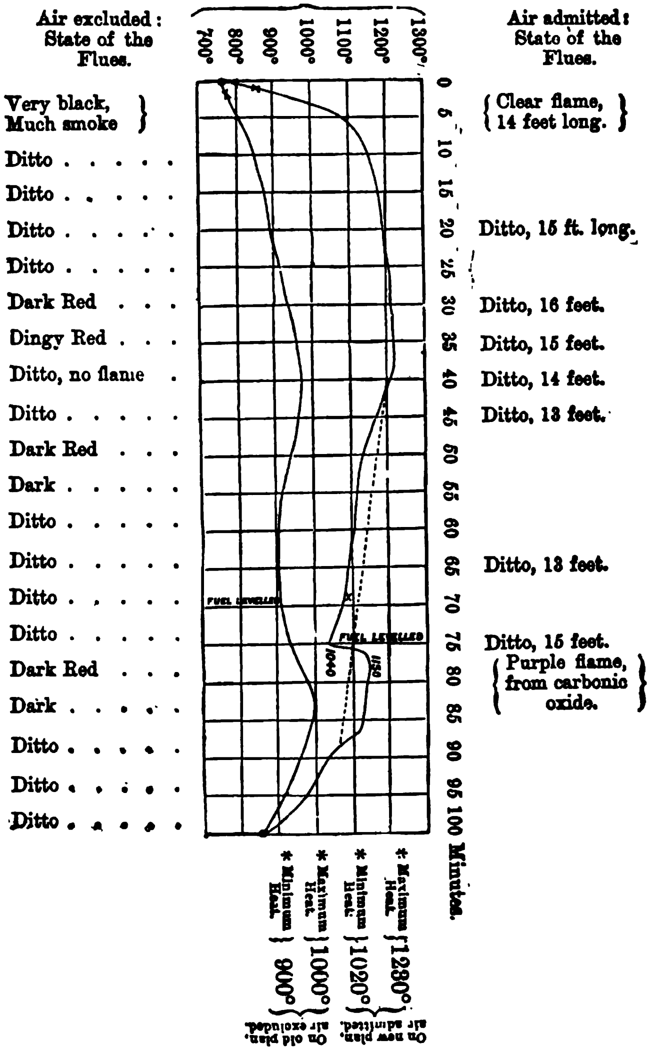

FIG. 69.—TEMPERATURE OF FURNACE.

chester meeting. As seen by reference to Fig. 69, the temperature in the flue fell to 750° F. (400° C.) on the introduction of a fresh charge of fuel, rose at the end of a half-hour

to above 1200° F. (650° C.), then fell, until at the end of an hour and a quarter it had dropped to 1040° F. (560° C.), the fire meantime not having been disturbed. On then levelling off the surface of the bed of fuel, and thus filling all holes in the fire, the temperature at once rose nearly to the maximum, and then gradually fell again to 850° F. (454° C.). During this period, the air was admitted above the fire; the lower line of the diagram shows the result of the usual method of handling the fires without air-supply above the fuel. The general method of variation of temperature is the same during the period between successive charges, but the temperature averages ten per cent lower. The transformation of a mass of black smoke into a flame many feet in length is the best possible evidence of the advantage of this operation. The gain in economy of fuel was estimated at about one third when the supply of air was properly adjusted and managed. The dotted line in the figure indicates the probable temperatures when the bed of fuel is kept level and free from holes.

82. Weather Waste.—When coal is exposed to atmospheric influences, a "weather waste" occurs. Oxygen is absorbed, and a slow combustion injures the fuel. Berthelot found also that at temperatures not exceeding 530° Fahr. (277° Cent.) hydrogen may be absorbed, and succeeded in converting two thirds of the bituminous coal experimented with into liquid hydrocarbons. Coals freshly mined give out gaseous hydrocarbons, and even anthracite mines, where deep, are not free from danger by the explosion of such gases. The absorption of oxygen, and this loss of hydrogen and carbon, is injurious to the fuel. According to Mursiller, coals containing "fire-damp" give it up at or below 626° Fahr. (330° Cent.), and lose their coking property. Coals usually absorb carbonic acid freely.

Poech concludes:* "Freshly-mined coal deposited on the rubbish piles is capable of condensing several times its volume of oxygen in its pores. The oxygen absorbed enters into chemical combination with the easily-oxidized constituents.

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* *Van Nostrand's Magazine*, 1884.

According as the absorption is rapid or slow, a greater or less elevation of temperature is produced. In the former it may lead to spontaneous combustion. The crumbling of coal is, among other causes, a consequence of the absorption and condensation of oxygen in its pores, and the chemical changes taking place. The escape of the hygroscopic moisture favors the absorption of oxygen. The pyrites can only produce a furthersome effect on the increase of temperature when present in considerable quantities, and then only in presence of moisture and air; in the dry state they must be regarded as perfectly passive, and may even be detrimental to the warming. Freshly-mined coal placed in an atmosphere of steam can suffer no change. Even with incomplete exclusion of the air the steam will, in general, oppose oxidation and warming, principally by uniform moistening of the pieces of coal."

83. The Composition of the Common Fuels may be obtained from the following tables:

COMPOSITION OF VARIOUS FUELS OF THE UNITED STATES.

	C.	*H.*	*O.*	*N.*	*S.*	Moisture.	Ash.	Spec. Grav.
Pennsylvania Anthracite.......	78.6	2.5	1.7	0.8	0.4	1.2	14.8	1.45
Rhode Island "	85.8	10.5		....	3.7	....	......	1.85
Massachusetts "	92.0	6.0		....	2.0	....	......	1.78
North Carolina "	83.1	7.8		....	9.1	....	......	.....
Welsh "	84.2	3.7	2.3	0.9	0.9	1.3	6.7	1.40
Maryland Semi-Bituminous.....	80.5	4.5	2.7	1.1	1.2	1.7	8.3	1.33
Penna. " "	75.8	20.2		....	....	....	4.0	1.32
" " "	59.4	38.8		....	....	....	1.8	1.30
Indiana " "	70.0	28.0		....	....	....	2.0	1.24
" " "	52.0	39.0		....	....	....	9.0	1.27
Illinois Bituminous.......	62.6	35.5		....	....	....	1.9	1.30
" (Block) Bituminous.....	58.2	37.1		....	....	....	4.7	....
Ill. and Ind. (Cannel) Bituminous	59.5	36.6		....	....	....	3.9	1.27
Kentucky " "	48.4	48.8		....	....	....	2.8	1.25
Tennessee Bituminous.........	71.0	17.0		....	....	....	12.0	1.45
" "	41.5	56.5		....	....	....	2.5	.....
Alabama "	54.0	42.6		....	1.0	1.2	1.2	.....
Virginia "	55.0	41.0		....	...	....	4.0	.....
" "	74.0	18.6		....	....	....	7.4	.....
Cal. and Oregon Lignite........	50.1	3.9	13.7	0.9	1.5	16.7	13.2	1.32

MONONGAHELA GAS COAL. (CRESSON.)

Weight of sample, 60 lbs. (27.27 kilogrammes).	
Volatile matter, per cent	35.74
Coke, per cent	64.26
Ash, per cent	6.66
Yield of gas, cubic feet per pound maximum	5.2
" " cubic metres per kilogramme maximum	0.324
Cubic feet per pound average	5.0
" " cubic-metres per kilogramme average	0.312
Ton maximum	11,648.0
" average	11,200.0
Illuminating power, 5 feet per hour = candles	15.0
" " 1 ton coal = lbs. sperm	576.0

COMPOSITION OF FOREIGN COALS.

	C.	*H.*	*N.*	*O.*	*S.*	Ash.	Specific Gravity.	Authority.
Welsh (Anthracite)	90.4	3.3	0.8	3.0	0.9	1.6	1.32	Vaux.
Scotch "	78.5	5.6	1.0	9.7	1.1	4.0	1.26	Muspratt.
English (Newcastle)	82.1	5.3	1.4	5.7	1.2	3.5	1.26	"
" (Lancashire)	77.9	5.3	1.3	9.5	1.4	4.6	1.27	"
" (Derbyshire)	79.7	4.9	1.4	10.3	1.0	2.7	1.29	"
" (Staffordshire)	78.6	5.3	1.8	12.9	0.4	1.0	....	Vaux.
French Anthracite	94.0	1.4	0.6	....	....	4.0	....	Jacqueline.
" Bituminous	84.0	5.0	1.0	8.0	....	2.0	1.33	Ledieu.
Spanish (Asturias)	53.0	40.0				7.0	....	Johnson.
German (Silesia)	57.9	42.0				2.1	1.26	"
Saxony	80.0	19.0				1.0	1.29	"
Prussia	56.7	18.9				24.4	1.47	"
Hindostan	50.0	35.4				14.6	1.37	"
Brazil	57.9	40.5				1.6	1.29	"
Nova Scotia	60.7	26.8				12.5	1.33	"
Cape Breton	67.6	26.9				5.5	1.34	"
Australia (Lignite)	64.3	4.2	1.0	10.0	0.6	10.0	1.27	Isherwood.
Borneo	70.3	5.4	0.7	19.2	1.2	14.2	1.37	Muspratt.
Chili	70.6	5.8	1.0	13.2	2.0	7.4	1.29	"
Coke	91.5	....	....	....	1.5	7.0	....	"

COMPOSITION OF SUNDRY FUELS.

	C.	*H.*	*N.*	*O.*	*S.*	Ash.	Specific Gravity.	Authority.
Wood (kiln-dried)	50.5	0.1	....	40.7	....	1.6	....	Watts.
" (air-dried)	40.4	4.9	0.9	32.7	....	1.2	0.5 to 1.2	"
Peat (kiln-dried)	60.0	6.8	1.3	30.0	....	1.9	....	Paul.
" (air-dried)	46.1	4.6	1.0	23.6	....	1.5	0.5	"
		Volatile Matter.						
Bitumen, United States	24.8	72.4				2.8	....	Johnson.
" England	52.2	47.5				0.3	....	"
" France	50.3	41.6				0.1	....	"
" South America	71.8	26.7				1.5	....	"
Asphaltum, Syria	24.4	68.0				7.6	....	"
" "	14.0	72.6				13.6	....	"
Petroleum, pure U. S.	86.0	14.0				....	0.8	
			Refuse.					
"Dead Oil"	86.5	7.0	1.5					
Gas, Marsh	75.0	25.0						Watts.
" Olefiant	85.7	14.3						

	Carb. Acid.	Carb. Oxide.	*H.*	*N.*	Hydro-carbon.	Authority.
Gas from Wood	11.6	34.5	0.7	53.2	....	Ebelmen.
" " Charcoal	0.8	34.1	0.2	64.9	....	"
" " Peat	14.0	22.4	0.5	63.1	....	"
" " Coke	1.3	33.8	0.1	64.8	....	"
" " Lignite	2.0	40.0	42.4	3.2	12.4	
" " Bituminous Coal*	4.1	23.7	8.0	61.5	2.2	Siemens.

* Burned in Siemens' gas-producers.

84. The Heating Effect, or calorific power of good specimens of the various kinds of fuel, is given in the following table, expressed in British thermal units:

CALORIFIC VALUE OF FUELS.

Fuel.	Calorific Power.		Water vaporized at Boiling-point, Parts by one Part.	Cubic Feet required to stow one Ton of Furnace Coal.	Weight. Pounds per Cubic Foot as stowed.
	Relative.	Absolute.			
Carbon, pure	1.000	14,500	15.00	......	....
Hydrogen	4.280	62,500	62.75	......	....
Marsh gas	1.816	26,415	26.68	......	....
Olefiant gas	1.466	21,328	21.54	......	....
Coal, Anthracite	1.020	14,833	14.98	40 to 45	49 to 56
" Bituminous	1.017	14,796	14.95	42 to 48	47 to 53
" Lignite, dry	0.7	10,150	10.35	42	53
Peat, kiln-dried	0.7	10,150	10.25	81	25
" air-dried	0.526	7,650	7.73	75	30
Wood, kiln-dried	0.551	8,029	8.10	......	....
" air-dried	0.439	6,385	6.45	56 to 100	22 to 40
Charcoal	0.930	13,500	14.00	......	....
Coke	0.940	13,620	14.00	56 to 75	30 to 40
Petroleum, heavy. W. Va.	1.250	18,200	18.75	45	50
" light, W. Va.	1.260	18,350	18.90	......	....
" " Penna	1.240	18,050	18.60	......	....
" heavy, Ohio	1.270	18,450	19.05	......	....
" Asia	1.240	18,000	18.60	......	....
" Europe	1.240	18,000	18.60	......	....
Shale Oil, France (crude)	1.240	18,000	18.60	......	....
Animal fat	0.650	9,000	9.30	......	....

The difference between theoretical and effective heating power for various kinds of fuel is exhibited in the following table, which gives the number of pounds of water evaporated by one pound of fuel, according to European authorities:

Fuel.	Heating Power.		
	Theoretical.	Under Steam Boilers.	Under Open Boilers.
Petroleum	16.30	10.0 to 14.0	....
Anthracite	12.45	7.0 to 11.0	....
Bituminous Coal	11.51	5.2 to 8.0	5.2
Charcoal	10.77	6.0 to 6.75	3.7
Coke	9.0 to 10.8	5.0 to 8.0	....
Lignite	7.7	2.5 to 5.5	1.5 to 2.3
Peat	5.5 to 7.4	2.5 to 5.0	1.7 to 2.3
Wood	4.3 to 5.6	2.5 to 3.75	1.85 to 2.1
Straw	3.0	1.86 to 1.92	....

RELATIVE VALUE OF VARIOUS WOODS. (OVERMAN.)*

Wood.	Specific Gravity.	Pounds in one Cord.	Per-centage Charcoal.	Specific Gravity of Charcoal.	Pounds of Charcoal in a Bush.	Relative Value of Wood.
Hickory, shell bark....	1.000	4.469	26.22	0.625	32.89	1.00
Oak, chestnut........	0.885	3.955	22.75	0.481	25.31	0.86
" white...........	0.885	3,821	21.62	0.401	21.10	0.81
Ash, white......... ..	0.772	3,450	25.74	0.447	28.78	0.77
Dogwood.............	0.815	3.643	21.00	0.550	29.94	0.75
Oak, black...........	0.728	3,254	23.80	0.387	20.36	0.71
" red..............	0.728	3,254	22.43	0.400	21.05	0.69
Beech, white..........	0.724	3,236	19.62	0.518	27.26	0.65
Walnut, black........	0.681	3,044	22.56	0.418	22.00	0.65
Maple, hard (sugar)....	0.644	2,878	21.43	0.431	22.68	0.60
Cedar, red............	0.565	2,525	24.72	0.238	12.52	0.56
Magnolia.............	0.605	2,704	21.59	0.406	21.36	0.56
Maple, soft.	0.597	2,668	20.04	0.370	19.47	0.54
Pine, yellow..........	0.551	2,463	23.73	0.333	17.52	0.54
Sycamore	0.535	2,391	23.60	0.274	19.68	0.52
Butternut	0.567	2,534	20.79	0.237	12.47	0.51
Pine, New Jersey.....	0.478	2,137	24.88	0.385	20.26	0.48
" pitch...........	0.426	1,904	26.76	0.298	15.68	0.43
" white....	0.418	1,868	24.35	0.293	15.42	0.42
Poplar, Lombardy....	0.397	1,774	25.00	0.245	12.85	0.40
Chestnut.	0.552	2,333	25.29	0.379	19.74	0.52
Poplar, yellow...	0.563	2,516	21.81	0.383	20.15	0.52

* Metallurgy. N. Y.: D. Appleton & Co., 1864.

Wood cut in January contains from 15 to 25 per cent less water than after the sap is in motion in April. As wood seasons naturally in the air, it loses from one sixth to one third its weight of water, but still contains from one seventh to one fourth its weight of moisture. A considerable part of the latter may be expelled by kiln-drying, and most of it if the kiln heat be raised to 212°. A cord of wood contains 128 cubic feet as it lies piled up. But allowing for the interstices in fairly piled wood, we may reckon a cord to actually contain about seventy-two cubic feet. Thoroughly dry wood weighs nearly as follows:

	One cubic foot.	One cord.
Hickory, pounds.........................	62	4,464
White oak...............................	53	3,816
White ash	49	3,528
Red oak	45½	3,276
White beech.............................	45	2,240

	One cubic foot.	One cord.
Apple tree	43	3,096
Black birch	43	3,096
Black walnut	42½	3,060
Hard maple	40	2,880
Soft maple	37	2,664
Wild cherry	37	2,664
White elm	36½	2,628
Butternut	35½	2,556
Red cedar	35	2,520
Yellow pine	34	2,447
White birch	33	2,376
Chestnut	32	2,304
White pine	26	1,872

With hickory at $5 a cord, other woods are worth about as below:

Hickory	$5 00
White oak	4 05
White ash	3 85
Apple	3 50
Red oak	4 45
White beech	3 25
Black walnut	3 25
Black birch	3 15
Hard maple	3 00
White elm	2 90
Red cedar	2 08
Wild cherry	2 75
Soft maple	2 70
Yellow pine	2 70
Chestnut	2 60
Butternut	2 55
White birch	2 40
White pine	2 10

Experiments on combustion, conducted by MM. Scheurer-Kestner and Meunier-Dollfus,* indicate that the method employed for determining the heating power of fuel, from its analysis, is not correct. A satisfactory explanation of this difference has not been given. The heating effect may depend

* *Bulletin de la Société Industrielle de Mulhouse*, 1868, 1869.

on the state in which the carbon exists in the coal; and that although the calorific effect of the combustion of charcoal has been determined, it may be higher in the case of other forms of carbon.*

Mr. G. H. Babcock gives the following tables as representative of familiar practice:

Kind of Combustible.	Air Required.	Temperature of Combustion.				Theoretical Value.		Highest Attainable Value under Boiler.	
	In lbs. per pound of of combustible.	With Theoretical Supply of Air.	With 1½ Times the Theoretical Supply of Air.	With Twice the Theoretical Supply of Air.	With Three Times the Theoretical Supply of Air.	In lbs. of Water raised 1° per lb. of Combustible.	In lbs. of water evaporated from and at 212°, with 1 lb. combustible.	With Chimney Draught.	With Blast, Theoretical Supply of Air at 60°, Gas 320°.
Hydrogen	36.00	5,750	3,860	2,860	1,940	62,032	64.20		
Petroleum	15.43	5,050	3,515	2,710	1,850	21,000	21.74	18.55	19.90
Carbon— Charcoal, Coke, Anthracite C'l	12.13	4,580	3,215	2,440	1,650	14,500	15.00	13.30	14.14
Coal— Cumberland	12.06	4,900	3,360	2,550	1,730	15,370	15.90	14.28	15.06
Coking bituminous	11.73	5,140	3,520	2,680	1,810	15,837	16.00	14.45	15.19
Cannel	11.80	4,850	3,330	2,540	1,720	15,080	15.60	14.01	14.76
Lignite	9.30	4,600	3,210	2,490	1,670	11,745	12.15	10.78	11.46
Peat— Kiln-dried	7.68	4,470	3,140	2,420	1,660	9,660	10.00	8.92	9.42
Air-dried, 25 p.c. water	5.76	4,000	2,820	2,240	1,550	7,000	7.25	6.41	6.78
Wood— Kiln-dried	6.00	4,080	2,910	2,260	1,530	7,245	7.50	6.64	7.02
Air-dried, 20 p.c. water	4.80	3,700	2,670	2,100	1,490	5,600	5.80	4.08	4.39

The above table gives the air required for complete combustion, the temperature attained with different proportions of air, the theoretical value, and the highest practically attainable value under a steam-boiler, assuming that the gases pass off at 320°, the temperature of steam at 75 lbs. pressure, and the incoming air at 60°; also, that with chimney draught twice, and with forced blast only, the theoretical amount of air is required for combustion.

The effective value of all kinds of wood *per pound*, when

* M. L. Gruner, *Engineering and Mining Journal*, xviii.

dry, is substantially the same. The following are the weights on other authorities of different woods by the cord :

Kind of Wood.	Weight.
Hickory, shell-bark	4,469
" red heart	3,705
White oak	3,821
Red oak	3,254
Beech	3,126
Hard maple	2,878
Southern pine	3,375
Virginia pine	2,680
Spruce	2,325
New Jersey pine	2,137
Yellow pine	1,904
White pine	868

The following table of American coals has been compiled from various sources:

Coal.		Per Cent of Ash.	Theoretical Value—	
State.	Kind of Coal.		In Heat Units.	In Pounds of Water Evaporated.
Pennsylvania	Anthracite	3.49	14,199	14.70
"	"	6.13	13,535	14.01
"	"	2.90	14,221	14.72
"	Cannel	15.02	13,143	13.60
"	Connellsville	6.50	13,368	13.84
"	Semi-bituminous	10.77	13,155	13.62
"	Stone's Gas	5.00	14,021	14.51
"	Youghiogheny	5.60	14,265	14.76
"	Brown	9.50	12,324	12.75
Kentucky	Caking	2.75	14,391	14.89
"	Cannel	2.00	15,198	16.76
"	"	14.80	13,360	13.84
"	Lignite	7.00	9,326	9.65
Illinois	Bureau County	5.20	13,025	13.48
"	Mercer County	5.60	13,123	13.58
"	Montauk	5.50	12,659	13.10
Indiana	Block	2.50	13,588	14.38
"	Caking	5.66	14,146	14.64
"	Cannel	6.00	13,097	13.56
Maryland	Cumberland	13.98	12,226	12.65
Arkansas	Lignite	5.00	9,215	9.54
Colorado	"	9.25	13,562	14.04
"	"	4.50	13,866	14.35
Texas	"	4.50	12,962	13.41
Washington Ter.	"	3.40	11,551	11.96
Pennsylvania	Petroleum	....	20,746	21.47

Mr. D. K. Clark thus assigns the several portions of the heat of combustion of good coke, as burned in the locomotive:*

Making steam	10,920 B. T. U.	73 per cent.
Loss at smoke-stack	2,316 "	16.5 "
Ash and waste	764 "	5.5 "
	14,000 B. T. U.	100 per cent.

and concludes that combustion in the furnace of the locomotive may be, and often is, practically perfect, and anticipates that economy in the formation of steam will only be improved by utilizing heat now wasted at the chimney. The usual maximum evaporation is about 8 times the weight of coke used —a low figure, which is mainly due to the comparatively small proportion of heating-surface adopted. The nearer the composition of the fuel approaches that of coke, the better, as a rule, the economical effect. Coal gives, as an average, about two thirds the effect of coke, as customarily burned; and its value may be fairly approximated, the composition being known, by assuming the carbon to be the only useful constituent.

ORDINARY CALORIFIC VALUES AS COMPARED WITH GOOD BITUMINOUS COAL.

	Lbs. Coal.
1 cord (3.62 cubic mètres) of seasoned hickory or hard maple	2,000
1 " " " " white oak	1,750
1 " " " " beech, red or black oak	1,500
1 " " " " poplar, chestnut, or elm	1,000
1 " " " " soft pine	960

85. Analyses of Ash.—The following analyses represent the character of ashes of anthracite and bituminous coals.

They may be taken as examples simply, since the ash of coal intended for metallurgical purposes should invariably be examined before taking the fuel for any important work.

ANALYSES OF ASH.

	Specific Gravity.	Color of Ash.	Silica.	Alumina.	Oxide Iron.	Lime.	Magnesia.	Loss.	Acids S.&P.
Pennsylvania Anthracite	1.559	Reddish Buff.	45.6	42.75	9.43	1.41	0.33	0.48	. ..
" Bituminous	1.372	Gray.	76.0	21.00	2.60	....	....	0.40	....
Welch Anthracite	1.32	......	40.0	44.8	....	12.0	trace	....	2.97
Scotch Bituminous	1.26	.....	37.6	52.0	....	3.7	1.1	....	5.02
Lignite	1.27	......	19.3	11.6	5.8	23.7	2.6	....	33.8

* Railway Machinery, p. 122.

Where the difference between two coals lies principally in their relative percentages of ash, the comparison is made in the manner about to be described.

The anthracites contain so little other combustible matter, that, as shown by Professor Johnson,* their calorific value is proportional very nearly to the percentage of contained carbon.

86. The Commercial Value of Fuels is somewhat modified by the depreciation produced by presence of non-combustible matter; this modification occurs in the following ways:

(1) A certain amount of carbon is required to heat the whole mass to the temperature of the furnace. Of this a large part is lost. It follows, therefore, that a coal containing a certain small quantity of combustible would have no calorific value, and consequently would be worthless in the market.

(2) The presence of a high percentage of ash in a fuel checks combustion by its mechanical mixture with the combustible portion of the coal. A coal will, hence, have no commercial value when the proportion of refuse reaches a limit at which combustion becomes impossible in consequence of this action.

(3) The cost of transportation of ash being as great as that of transporting the combustible, the consumer paying for ash at the same rate as for the carbon, and also being compelled to go to additional expense for the removal of ash; these facts also determine a limit beyond which an increased proportion of ash renders the fuel valueless.

(4) The determination of the financial losses due to increased wear and tear of furnaces and boilers, of incidental losses due to inequality or insufficiency of heat-supply, and to the many other direct and indirect charges to be made against a poor fuel, also indicate a limit which has a different value for each case, but which, in most cases, is difficult of even approximate determination. The determination of the minimum proportion of combustible, under the first case, is made as follows, assuming this heat to be entirely wasted:

(*a*) The specific heat of ash is usually nearly 0.20. Let X

* Report to the Navy Department on American Coals.

represent the percentage of ash which is sufficient to render the coal valueless. Then, since each pound of carbon has a heating-power of 14,500 British thermal units (3625 calories), $14,500 (100 - X) = A$, represents the available heat of a unit in weight of the fuel; $100 \times 0.20 \times 3000° = B$, represents the heat required to raise this same amount of coal to a temperature equal to that of the furnace, which is here assumed at 3000° Fahr. (1633° Cent.) above the surrounding atmosphere.

Since these quantities A and B are equal: $14,500 (100 - X) = 100 \times 0.2 \times 3000°$, and $X = 96$ per cent.

The minimum quantity of fuel permissible is, therefore, four per cent, where the first consideration only is taken into the account.

(*b*) The influence of the second condition is at present not determinable in the absence of experiment.

(*c*) The cost of transportation of ash to the consumer, as a part of the fuel, is not taken in the determination of its value to him. The removal of ash is a tax upon the consumer which may be considered as the equivalent of the loss of a certain weight of combustible received. Since this cost fluctuates with the market value of coal, and since its amount is determined by the same causes, it is easy to make the statement in that form. This cost is about ten per cent of the value of coal, weight for weight, and is therefore assumed at ten per cent of the proportion of ash found in the coal.

(*d*) The losses, direct and indirect, coming under the fourth head, vary greatly, and are sometimes very serious. An approximate estimate for an average example is taken, and is considered to be equal, at least, to a percentage of the total value of coal, in utilizable carbon, which equals one half the percentage of ash. Comparing two anthracites, which we will suppose to contain, respectively, fifteen and twenty-five per cent ash, eighty-five and seventy-five per cent carbon, the first being a well-known standard coal, selling in the market at six dollars per ton (1016 kilogrammes), we may, using this system of charging losses against equivalent values in combustible carbon, determine the proper commercial value of the second kind.

First Example.—From the 85 per cent carbon:

Deduct for heating to furnace temperature	0.040
" " transportation of refuse 10 per cent of 15	0.015
" " other losses 50 per cent of 15	0.075
Total	0.130

leaving valuable and available carbon $85 - 13 = 72$ per cent.

Second Example.—From the 75 per cent carbon:

Deduct for heating to furnace temperature	0.040
" " removal of ash 10 per cent of 25	0.025
" " sundry losses 50 per cent of 25	0.125
Total	0.190

leaving valuable available carbon $75 - 19 = 56$ per cent.

Finally, if $6.00 is paid for 72 per cent available combustible, for 56 per cent we should pay $\frac{56 \times 6}{72} = \$4.66\frac{2}{3}$.

Third Example.—Taking a third example, in which the fuel contains the exceptionally large proportion of 30 per cent ash, we should, by similar method, proceed as follows, deducting from the seventy per cent carbon as before the estimated charges against it:

Deduct for heating	0.040
" " removal of ash 10 per cent of 30	0.030
" " sundry expenses 50 per cent of 30	0.150
Total	0.220

leaving available carbon, $70 - 22 = 48$ per cent, which would be worth $\frac{48 \times 6}{72} = \$4.00$.

Had the first coal had a market value of seven dollars per ton, the second and third would have been worth, respectively, $5.44½ and $4.66⅔.

Expressing this operation by symbols, if V represents the value of the fuel in percentage of pure carbon, and A equal the percentage of ash, $V = 0.96 - 1.60A$.

This method is evidently largely empirical, and its results

are but approximate. It is, however, simple and easily applied, and will often be found of use in the absence of more precise means of determination.

The kind and quality of fuel employed in the production of steam for commercial purposes is often determined by conditions quite independent of the special quality of the fuel. In most cases the element of cost is the controlling one.

Johnson, in his report to the Navy Department (1844) on American coals, proposes to grade coals according to—

(1) Their relative weights.
(2) Rapidity of ignition.
(3) Completeness of combustion.
(4) Evaporative power under equal weights.
(5) Evaporative power under equal bulks.
(6) Evaporative power of combustible matter.
(7) Freedom from waste in burning.
(8) Freedom from tendency to form clinker.
(9) Maximum evaporative power under equal bulks.
(10) Maximum rapidity of combustion.

He found it impossible to select any one coal which could be placed first in all these qualities or to attach equal importance to all. For steam navigation he attaches most importance to the fifth, "the evaporative power for equal bulks," as stowage-space is supremely important in steam navigation. With the fifth he combines the eighth and tenth, viz., "freedom from clinker" and "maximum rapidity of action." American coals are usually superior to foreign coals.

87. Good Furnace Management, to secure maximum heat-supply from the unit weight of fuel, is evidently as essential to economy and efficiency of steam production as choice of proper fuels.

In the management of the furnace the effort should be made to secure the best conditions for economy, and as nearly as possible perfect uniformity of those conditions. The fuel should be spread over the grate very evenly, and the tendency to burn irregularly, and especially into holes or thin spots, should be met by skilful "firing," or "stoking" as it is also termed, at such intervals as may by experience be found best.

The smaller the coal, where anthracite is used, the thinner should be the fire; the stronger the draught the thicker the bed of fuel, of whatever kind. With too thin a fire, the danger arises of excess of air-supply; with too heavy a fire, carbon monoxide (carbonic oxide) may be produced. In the former case combustion will be complete, but the heat generated will be distributed throughout the diluting excess of air, and thus rendered less available, and the efficiency of the furnace will be correspondingly reduced; while in the latter case a loss arises from incomplete combustion, and waste takes place by the passage of combustible gas up the chimney. The second is the less common cause of loss of the two, but both are liable to arise in almost any boiler, and we may even have both losses exhibited in the same boiler and at the same time. Successful working demands a very perfect mixture of the combustible with the supporter of combustion, and should this not be secured, serious waste will take place.

The appearance of smoke at the chimney-top is not always indicative of serious loss, nor is its non-appearance always proof of complete combustion. With soft coals and other fuels containing the hydrocarbons some smoke usually accompanies the best practically attainable conditions; anthracites, charcoal, and coke never produce true smoke. Attempts to improve the efficiency of a heat-generating apparatus by "burning the smoke" usually fail by introducing such an excess of air as to cause a loss exceeding that before experienced from the formation of smoke. Thorough intermixture of a minimum air-supply with the gases distilled from the fuel is the only means of attaining high efficiency.

In firing, or stoking, especial care should be taken to see that the sides and corners of the grate are properly attended to. Regulation of the fire is best secured by the careful adjustment of the damper. The manipulation of the furnace doors for this purpose is likely to cause waste. Liquid fuels are especially liable to waste by excessive air-supply, and gaseous fuel exhibits a peculiar liability to the opposite method of loss; both should be, if possible, even more carefully handled than any solid fuels.

88. The Fuels, Boiler, and Furnace must be adapted each to the others very carefully, if the best results are to be attained. Soft, free-burning fuels demand a different form of grate, as well as different air-distribution and furnace management, from the hard and slow-burning combustibles. The form and size of furnace, the extent and kind of heating-surface, and the type of boiler even, all influence the total efficiency of steam generation. Tubular boilers have small flues or tubes, and are better fitted for use with anthracite coal and with coke or other fuels burning with little flame; while larger tubes or flues are better adapted for use with the bituminous and other soft, long-flaming combustibles. It thus happens, for example, that a locomotive using anthracite coal, another engine burning bituminous coal, and a coke-burning engine, all have different proportions of boiler.

CHAPTER IV.

HEAT—PRODUCTION; MEASUREMENT; TRANSFER; EFFICIENCY OF HEATING-SURFACE.

89. **The Nature of Heat**, long debated among men of science, has in the course of the last century become well determined. Heat consists in the vibrations of the molecules of which bodies are composed, and is a form of energy. This energy, although actually kinetic, being molecular is often taken to be potential or latent. The two forms in which energy is stored, when heat is communicated to any substance, are "sensible heat," of which the intensity is exhibited by the thermometer, and which is measured in quantity by the various methods of calorimetry; and "latent heat," which is not detected or measurable as heat, and which in fact does not exist as heat, but has been transformed into the true potential energy of changed physical state and altered molecular relations: it is manifested by a change of volume in the body affected.

Thus all masses, of whatever kind, composition, or form, when heated increase in temperature and are altered in volume, and the sum of the heat-energy producing the change in temperature and the potential energy measured by the product of the change of volume and the total intensity of the forces, internal and external, resisting that change measures the total heat transferred to effect the physical changes noted. The sensible heat retains its original form; the latent heat, so-called, is no longer heat at all, but may be retransformed and may again appear as heat on reversing the first operation of transfer. In solids, by far the greater part of the heat received remains sensible, and takes effect in producing change of temperature; in the transformation of the solid into liquid by fusion all heat absorbed becomes latent, and produces ex-

pansion of volume; in heating the liquid the heat is employed mainly in elevation of temperature, but in part in doing work with the result of transformation into latent heat. During vaporization at any fixed temperature all heat is disposed of in causing change of volume, and this is known as the "latent heat of evaporation," or of vaporization; while in the expansion of vapors and gases the increase of volume continues to be comparatively large in amount, and the "latent heat of expansion" is a correspondingly large proportion of the total, and is especially large in vapors, such as steam, which have great internal potential energy due to the action of powerful molecular attractive forces. The heat-energy demanded to make steam in the boiler is thus, at ordinary temperatures, ten times greater than that required to overcome the external pressure measured by the steam-gauge.

90. Production of Heat by Combustion and other methods involves, in all cases, the expenditure of an equivalent amount of energy in some transformable shape.

The original source of all heat-energy is found far back of its first appearance in the steam-boiler. It had its origin at the beginning, when all Nature came into existence. After the solar system had been formed from the nebulous chaos of creation, the glowing mass which is now called the sun was the depository of a vast store of heat-energy, which was thence radiated into space and showered upon the attendant worlds in inconceivable quantity and with unmeasured intensity. During the past life of the globe the heat-energy received from the sun upon the earth's surface was partly expended in the production of great forests, and the storage, in the trunks, branches, and leaves of the trees of which they were composed, of an immense quantity of carbon, which had previously existed in the atmosphere, combined with oxygen, as carbonic acid. The great geological changes which buried these forests under superincumbent strata of rock and earth resulted in the formation of coal-beds, and the storage, during many succeeding ages, of a vast amount of carbon, of which the affinity for oxygen remained unsatisfied until finally uncovered by the hand of man Thus we owe to the heat and light of the sun,

as was pointed out by George Stephenson, the incalculable store of potential energy upon which the human race is so dependent for life and all its necessaries, comforts, and luxuries.

This coal, thrown upon the grate in the steam-boiler, takes fire, and, uniting again with the oxygen, sets free heat in precisely the same quantity that it was received from the sun and appropriated during the growth of the tree. The actual energy thus rendered available is transferred, by conduction and radiation, to the water in the steam-boiler, converts it into steam, and its mechanical effect is seen in the expansion of the liquid into vapor against the superincumbent pressure. Transferred from the boiler to the engine, the steam is there permitted to expand, doing work, and the heat-energy with which it is charged becomes partly converted into mechanical energy, and is applied to useful work in the mill or to driving the locomotive or the steamboat.

Thus we trace the store of energy received from the sun and contained in the fuel through its several changes until it is finally set at work; and we might go still further and observe how, in each case, it is again usually retransformed and again set free as heat-energy.

The transformation which takes place in the furnace is a chemical change; the transfer of heat to the water and the subsequent phenomena accompanying its passage through the engine are physical changes, some of which require for their investigation abstruse mathematical operations. A thorough comprehension of the principles governing the operation of the steam-boiler can only be attained after studying the phenomena of physical science with sufficient minuteness and accuracy to be able to express with precision the laws of which those sciences are constituted. The study of the philosophy of the generation and application of steam involves the study of chemistry and physics, and of the new science of energetics, of which the now well-grown science of thermo-dynamics is a branch.

These sciences, like the steam-engine itself, have an origin which antedates the commencement of the Christian era; but

they grew with an almost imperceptible growth for many centuries, and finally, only a century ago, started onward suddenly and rapidly, and their progress has never since been checked. They are now fully-developed and well-established systems of natural philosophy. Their consideration is the special province of works on the physical sciences and on applied mechanics.

Combustion is simply the union of some combustible with oxygen; but this phenomenon involves both chemical and physical operations. The first operation is a physical phenomenon: it consists in the elevation of the temperature of one or both constituents of the compound to be formed, until, by some as yet not clearly understood modification of their molecular relations, their chemical affinities come into play and combination takes place. But this combination consists in the enforced approximation of molecule to molecule, a relative motion taking place of great rapidity, and work is thus done of considerable amount. The resulting collision converts this energy of molecular motion into that energy of molecular vibration familiar to us as heat, and the quantity of heat so produced is the measure of the potential energy of chemical affinity in which it has its origin. With its development in this form this energy assumes an available and manageable form, and becomes at once capable of application to the purposes of the engineer. It may now be measured, stored, transferred wherever wanted, and finally, as required, transformed into mechanical energy, and in that form applied to all kinds of useful work.

91. Temperatures and Quantities of Heat are related to each other as are pressures and work in dynamics. The one is a factor of the other, but the first is not a measure of the second. Temperature measures the intensity of molecular heat-vibrations and the tendency of heat-energy to transfer itself to another body, very much as the pressure or tension of a confined gas or of steam measures the tendency to expand. In fact, the pressure of a confined gas and the total internal and external pressure of a vapor or other substance are directly and precisely proportional to the temperature, measured from the absolute zero of heat-motion.

Quantity of heat is the measure of the energy, whether in heat-units or in equivalent mechanical units,—thermal units, calories, or foot-pounds,—of the heat transferred in any change. It is equal to the product of the weight of the mass affected, its specific heat and the range of temperature marking the change.

Temperatures are measured in either Fahrenheit or centigrade degrees, and on either the common or the absolute scale. On the Fahrenheit thermometric scale the range of temperature between the two standards, the melting-point of ice or the freezing-point of water, under normal atmosphere and pressure, and the boiling-point of pure water under one atmosphere, is divided into 180 equal parts or degrees, and the zero is conventionally placed thirty-two degrees below the former point, the freezing and boiling points thus being found at 32° Fahr. and 212° Fahr., respectively. On the centigrade thermometer the range between the standard temperatures is made 100°, and the zero is taken conventionally at the lower of these two temperatures, the freezing and boiling points being thus at 0° Cent. and 100° Cent., respectively.

The "*absolute scale*" of temperatures is one on which it is sought to place the zero-point at the absolute zero of heat-motion—at that point at which all heat-energy becomes zero and temperature ceases to have existence. This is found to be at very nearly $-461°.2$ Fahr., or $-274°$ Cent.; so that, on the absolute scale, the standard temperatures are $+393°.2$ Fahr. and $+573°.2$ Fahr., or $+274°$ Cent. and $+374°$ Cent. It is found that the scale of the air-thermometer is sensibly coincident with the absolute scale, provided its readings are made proportional to the volumes of the enclosed gas at the several temperatures. Calling T the temperature on this scale the characteristic equation $\frac{pv}{T} =$ constant is found correct for all true gases, p and v being the pressure and volume of unity of weight at any assumed temperature, T; hence for the air-thermometer, in which p is constant, $v \propto T$.

The Thermal Unit, the unit by which quantity of heat is measured as heat, is that amount of heat-energy which is de-

manded to raise the temperature of unity of weight of water from the temperature of maximum density to one degree above that point. The British thermal unit is measured, customarily, by the engineer, by the "pound-degrees," and quantities of heat are measured by the number of such thermal units transferred. The metric thermal unit or "calorie," as it was called by the French philosophers who first adopted the metric system, is that quantity of heat which is required to raise the temperature of one kilogramme of water one degree centigrade,— the "kilogramme-degree."

Specific Heat is the quantity of heat in thermal units demanded by unity of weight of any given material, as of water to raise its temperature one degree. When this heat is all sensible, it is simply called specific heat, but when it is in any observable amount latent, as in expansion of gases, a distinction must be made between the "Specific Heat at Constant Volume," which is the real specific heat, and the "Specific Heat at Constant Pressure," and other specific heats involving more or less transformation of heat in the performance of the work of expansion. The specific heats of the gases are given in § 78 for constant pressure. Those of the solids are given in the following table:

SPECIFIC HEATS OF METALS AND MINERALS.

Iron	0.11379	acc. to Regnault,	0.1100	acc. to Dulong and Petit.
Zinc	0.09555	" "	0.0927	" " "
Copper	0.09515	" "	0.0949	" " "
Brass	0.09391	" "	......	" " "
Silver	0.05701	" "	0.0557	" " "
Lead	0.03140	" "	0.0293	" " "
Bismuth	0.03084	" "	0.0288	" " "
Antimony	0.05077	" "	0.0507	" " "
Tin	0.05623	" "	0.0514	" " "
Platinum	0.03243	" "	0.0314	" " "
Gold	0.03244	" "	0.0298	" " "
Sulphur	0.20259	" "	0.1880	" " "
Coal	0.24111	" "		
Coke	0.20307	" "		
Graphite	0.20187	" "		
Marble	0.20989	" "		

Unslaked Lime.	0.2169	according to Lavoisier and Laplace.	
Oak-wood	0.570	"	" Mayer.
Glass...........	0.19768	"	" Regnault.
Mercury........	0.03332	"	" "

Laplace and Lavoisier employed the method by melting; Dulong and Petit, the cooling method; Pouillet, and recently also Regnault, the method by mixture, which seems to be the most accurate method.

Coke, coal, masonry, and the stones and earths may be taken as averaging very closely $c = 0.20$. The woods range from $c = 0.50$ to $c = 0.65$.

The specific heat of the same material, as has been seen, is not perfectly constant, but increases as the temperature increases. Thus, according to Dulong and Petit, the mean specific heat is as follows:

Iron.............	between 0° and 100°,	0.1098;	between 0° and 300°,	0.1218
Mercury..........	" " "	0.0330;	" " "	0.0350
Zinc...............	" " "	0.0927;	" " "	0.1015
Copper.............	" " "	0.0947;	" " "	0.1013
Platinum...........	" " "	0.0335;	" " "	0.0355
Glass...............	" " "	0.1770;	" " "	0.190

Regnault found the ratio between the freezing and boiling points of the gases to be:

	Constant Volume.	Constant Pressure.
Air..	1.3665	1.3670
Hydrogen..................................	1.3667	1.3661
Nitrogen..................................	1.3668	......
Carbonic Acid............................	1.3688	1.3669
Carbonic Oxide...........................	1.3667	1.3719
Nitrous Oxide............................	1.3676	1.3719
Cyanogen..................................	1.3829	1.3877
Sulphurous Acid.........................	1.3843	1.3903

A relation between the specific heat and the atomic weight originally established by Dulong and Petit, and confirmed by Regnault, is very interesting. The product of the specific

heats and the atomic weights is nearly constant, and varies only from 38 to 42; thus:

	C.	At. Wts.	Products.
For Iron....................	0.11379	339.21	38.597
" Silver....................	0.05701	675.80	38.527
" Platinum................	0.03243	1233.5	39.993
" Sulphur..................	0.20259	201.17	40.754

92. **Thermometry and Calorimetry** are the processes employed by physicists and engineers in the quantitative determination of temperatures, and of quantities of heat and their variations. The instruments employed consist of the various kinds of thermometers and pyrometers for measuring temperatures, and of several sorts of calorimeter, the form being determined by the character and accuracy demanded by the work to be done.

Thermometers usually consist of a bulb, commonly of glass, and a capillary stem which the fluid inclosed traverses as its volume changes, the position of the head of the column at any moment indicating the temperature attained by the instrument at the instant, the reading being taken from a scale established by the maker and standardized by reference to the standard temperatures or by comparison with another instrument of known accuracy.

Mercury is generally used in thermometers ranging from below the freezing-point up to about 500° Fahr. (260° Cent.). For the extremely low temperatures at which mercury might freeze, alcohol is used, and it may be employed also for familiar atmospheric temperatures. For temperatures approaching or exceeding the boiling-point of mercury, the various metallic thermometers or "pyrometers" are used, which depend for their operation upon differences in the rates of expansion of two metals. Siemens' electric pyrometer depends for its action on the variation of the resistance of a conductor of electricity with variation of temperature.

The finer kinds of thermometer used in the thermometry of the engineer are mainly employed in the determination of temperatures of air and water, in the measurements connected

with steam-boiler trials. They are always mercurial thermometers, and are made and standardized with the utmost possible accuracy; those used in the calorimeters employed in determining the character of the steam furnished by boilers are often graduated to tenths, or even to twentieths, of degrees. The pyrometers used by the engineer are commonly constructed of a tube inclosing a rod of a different metal, the two secured together at one end, while at the other end the tube carries a case and dial, and the rod actuates a pointer, through some system of multiplying gear. The tube is usually of iron, and the rod of brass or copper. A more sensitive form is that in which the disposition of the two metals is reversed. The special forms of calorimeter used in connection with boiler tests will be described later.

Regnault's and Wiedemann's experiments, made on simple gases, and on carbonic oxide which is formed without condensation, proved that in these cases the specific heat between 0° and 200° C. is constant; whilst their experiments on gases formed with condensation show that the specific heat varies, the mean being given in the following empirical formulæ:

For	CO_2 =	44 gr. C.	=	$8.41 + 0.0053t$	Mean of Regnault
"	NO =	44 "	=	$8.96 + 0.0028t$	and Wiedemann.
"	C_2S_4 =	76 "	=	$10.62 + 0.007t$,	Regnault.
"	NH_3 =	17 "	=	$8.51 + 0.00265t$,	Wiedemann.
"	C_4H_4 =	28 "	=	$9.42 + 0.0115t$,	Wiedemann.

93. **The Transfer of Heat** from the furnace to the boiler involves the application of chemical and physical principles which will be briefly stated in a succeeding part of this chapter. The production of heat by the chemical processes involved in construction has been seen to be governed by the nature of the fuel, by the relative proportion of combustible and of supporter of combustion, and by the quantity of diluting gases present. The heat, once produced, is the more completely available as the temperature of the products of combustion is higher; it is the more completely utilized, also, as the arrangements for its transfer are the more complete and effective.

The utilization and the waste of heat are dependent upon

the method and extent of its transfer to the absorbing apparatus, or to other bodies. The heat generated in the furnace of a steam-boiler is usually mainly transferred to the boiler by radiation, conduction, and convection, partly, often in somewhat large proportion, to the chimney and the outer air by convection, and to some extent to adjacent objects by conduction or radiation through the furnace-walls and the occasionally opened furnace-doors. The laws and the extent of these utilizations or wastes are fairly well understood, and can be sometimes calculated with a satisfactory degree of accuracy and certainty.

The tendency to transfer heat by either of the three methods, radiation, conduction, or convection, and the quantity so transferred, depend upon—

(1) The difference of temperature between the source and the receiver of that heat.

(2) The extent and character of the surfaces between which such transfer takes place.

(3) The extent and nature of the intervening body or bodies.

It is usually assumed that it is sensibly correct to take the quantity transferred, in any case, as measured by the product of the difference of temperature by a coefficient obtained for each substance by experiment.

94. **Radiation of Heat** is the direct transfer of that form of energy from one body to another across intervening space, the only medium of transfer being the "luminiferous ether," the waves in which act as the vehicles of transportation, travelling at the rate of 186,860 miles (300,574,000 m.) per second. The vibrations of dark, pure heat-waves occur at the rate of 400,000,000,000,000 per second or less; those of greater frequency, up to about double this rate, are light-waves; and still more rapid vibration constitutes the actinic or chemical ray. The slowest heat-rays have about one fourth the rate of the fastest; and the most rapid of known actinic rays vibrate one hundred times as rapidly as these last. Visibly hot bodies emit all kinds of rays. All bodies are continually receiving

and emitting heat-rays, and, according to Prevost's theory of exchanges, gain or lose in total heat and in temperature accordingly as they gain by absorption from surrounding bodies more than they yield to the latter, or the reverse.

A good radiator is always a good absorbent. Any body which absorbs a particular kind of ray will, when emitting energy, radiate the same form. Diathermous substances permit the heat-rays to pass through, as transparent substances admit light-rays: but diathermous bodies are not necessarily equally, even if at all, transparent; and all substances are more diathermous to some rays than to others, while good absorbents are not diathermous.

Radiation plays an important part in the operation of the steam-boiler, in the furnace of which, when the fire is bright, it is estimated that usually about one half of all the heat taken up by the generator is received direct from the fuel by radiation.

95. **Conduction** is the method of transfer of heat by flow from part to part in the same body, or from one to another of bodies in contact. These two phenomena are not precisely the same. The flow of heat from a hot to a cold body in contact depends not only upon the conducting power of the two substances, but also, and often mainly, on the condition of the touching surfaces and the perfection of their contact. The rate of transfer within any given material depends solely on the variation of temperature along the line of flow, and on the character of the substance.

Conductivity measures the rate of flow, or of transfer of heat, under any assumed and defined conditions; it is the power of transmission of heat. The rate of conduction, or the conductivity, may be expressed by the number of thermal units passing across a surface, or through an internal section, in the unit of time; it is proportional to the rate of variation of temperature along the line of flow and to the constant coefficient denominated the conductivity, or the *coefficient of conductivity*. Thus the quantity, Q, of heat passing in any given time, t, is measured by the product of that time into the con-

ductivity, k, and into $\frac{dT}{dx}$, the rate of variation of temperature with distance traversed, and area of section, A,

$$Q = Akt\frac{dT}{dx}. \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (1)$$

The value of k varies greatly with different substances, being comparatively high with the metals and very low with all organic materials and the minerals. Where k is constant, the equation above given becomes

$$Q = Akt\frac{T_1 - T_2}{x}. \quad . \quad . \quad . \quad . \quad . \quad . \quad (2)$$

Where, as is often the case, the thermal resistance instead of the conductivity is taken, we shall have, when r is the coefficient of resistance, $r = \frac{1}{k}$, and

$$Q = \frac{(T_1 - T_2)At}{rx}; \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (3)$$

and the following values of r are found by experiment, according to Peclet, for x in inches and Q in British thermal units per hour:*

Gold and silver	0.0016
Copper	0.0018
Iron	0.0043
Zinc	0.0045
Lead	0.0090
Stone	0.0716
Brick	0.1500

Where the plate consists of laminæ, each may be considered by itself, and the total resistance obtained by adding together the resistances of the several parts.

* *Vide* Rankine's Steam-engine, p. 259.

The surface resistance forms so large a part of the total in steam-boiler practice, that the formula

$$Q = \frac{(T_1 - T_2)^2 At}{a} \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (4)$$

may be conveniently used to compute the amount of heat transferred, a being taken as from 150 to 200 in British measures (15 to 20 in metric measures), accordingly as the surfaces are clean or not, the plate being of iron, with water on one side and hot gases on the other A = sq. ft.; t = hrs.

96. Convection of Heat occurs by its communication to the particles of a fluid, and then by the flow of those particles into new positions, and by their contact with the receiver of heat by the transfer of that heat to such receiver. Convection is the only method of transfer in liquids, since conductivity is not appreciable, and it is only by its transportation by means of currents that it can be transferred at all. A good circulation is therefore essential to rapid transfer, and the rate of transfer is thus in a sense proportional to the efficiency of circulation. Thus the efficiency of a steam-boiler is dependent upon the effectiveness of its circulation, as well as upon the extent and conductivity of its heating-surfaces. A quiescent mass of water or of gas is incapable of transferring heat, and that element can only pass such a mass by penetrating it as radiated energy, its vehicle being the ether, which pervades all diathermic substances. Heat applied to the surface of still water does not pass downward at all or in any direction by real conduction; applied at one side or at the bottom of the mass, currents are at once set up, by means of which a rapid upward transfer of heat may take place. Thus convection invariably produces transportation of heated particles, and transfer of heat, from the source of heat to a receiver of heat, or a refrigerator, at a higher level. For best effect the heat must in all cases be applied at the lowest part of the fluid mass. These facts and deductions are equally true of liquids and gases, the latter being even more perfect non-conductors than the former.

Condensation of steam and other vapors by contact with cooling surfaces at temperatures below those of vaporization always occur by a peculiar convection, the circulating or moving currents of vapor streaming toward the refrigerating surfaces, these streams having their origin in the condensation of the vapor in contact with the latter, and the formation thus of a vacuous space into which they are driven by the elasticity of the fluid. A continuous condensation and steady flow is produced, and is sustained as long as these conditions persist. This operation is the most rapid of all known methods of convection or of transfer of heat, the mobility of the vapor permitting the most rapid movement of its currents, and its instantaneous condensation preserving a constant head which forces the fluid in the direction of the condensing surface on which it is converted into a liquid of comparatively small volume and capable of prompt and complete removal.

97. **The Transfer of Heat in Boilers** is due to convection largely. It is obvious that where transfer of heat takes place from one fluid to another through the sides of a containing vessel, as in the steam-boiler, or the surface-condenser of the marine steam-engine, the two fluids should be so circumstanced that their currents should flow in opposite directions, the heating or the cooled fluid entering on the heating-surface of the boiler or other vessel at its point of maximum temperature, and passing off at the coolest part; while the cooling or heated fluid, the receiver of heat, should come into contact with the separating sheet of metal at its coldest part and pass off at the hottest. In the steam-boiler the feed-water should enter at that part at which the furnace-gases are entering the chimney-flue, and should circulate toward the furnace. In the surface-condenser the condensing water should enter near where the water of condensation is taken away by the pumps, and should issue near the point at which the steam enters. It is further evident that in the latter case, other things being equal, that disposition of apparatus which permits most rapid and complete removal of the drops and streams of water of condensation from the cooling surfaces, so as to give at all times the maximum possible area of effective surface, will pro-

duce the highest efficiency. This has been found practically of essential importance in the design and construction of such condensing apparatus.

Feed-water heaters for the above-stated reasons are placed in the chimney-flue, while superheaters are sometimes placed in the furnace. Considerations of convenience and economy, however, oftener compel the designing engineer to place the latter at the exit of the furnace gases from the boiler and between the latter and the feed-water heater. As a rule, however, the rapidity and completeness of the circulation of the waters in a well-designed boiler are such that the point of introduction of feed-water is a matter of minor importance, so far as the boiler itself is concerned; and the engineer usually seeks to enter the feed in such a manner as shall evade risk of injury by irregular strains due to excessive differences of temperature in its different parts. The mass of water in a good boiler, freely steaming, may be assumed to have substantially uniform temperature, and only the furnace gases need be considered as flowing in definite paths with varying temperature. The use of the "counter current, as it is called, is better illustrated practically in the case of the condenser.

Experience shows that the thickness of the intervening plate has practically no important influence, as a rule, on the efficiency of transfer. Thick furnace-flues and thin tubes in the steam-boiler seem about equally effective; and the Author has known cast-iron condenser-tubes to work practically with the same efficiency as the thin brass tubes, of one quarter their thickness, customarily employed. It should be stated, however, that sheets of iron or steel in the furnaces of boilers, or in flues where exposed to nearly furnace temperatures, are liable to injury by "burning," if very thick, and especially if the laps of their seams are so exposed. In some cases the law forbids the use of heavy plates in furnace-flues or parts exposed to flame.

98. Efficiency of Heating or Cooling Surface measures the ratio of actual amount of heat transmitted across such surface to the total quantity available for such application; in steam-boilers it is the ratio of the quantity of heat utilized in

heating and vaporizing the fluid to the total which is produced by the furnace, the unutilized heat being wasted by conduction and radiation to other bodies, or sent up the chimney. An expression was found by Rankine, based upon equation (4) of article 95, which has been found to give very satisfactory results when properly used in application to the ordinary work of steam-boilers. This expression may be derived as below.

Let w be the weight of furnace-gases discharged per hour, $T - t$ the difference between the temperatures of gas and water on opposite sides of any part of the plate on the elementary area dS, C the specific heat of the gas, and let q be the quantity of heat passing across unity of area in unity of time for a difference in temperature $T - t$, in other words, the "rate of conduction" per unit of area per hour.

The quantity of heat transferred across the area dS is then equal to qdS, and the fall of temperature of gas must be this quantity divided by the product of the weight, w, and specific heat, C, of the gas from which the heat is derived,

$$\frac{qdS}{Cw} = - dT; \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (1)$$

and the gas flows on to the next elementary area and beyond, surrendering its heat as it goes, until it finally leaves the absorbing surface and enters the chimney-flue.

If T_1 and T_2 are the initial and final temperatures of the gas, and t the temperature of the water entering the boiler, the heat produced, Q_1, and that wasted, Q_2, per hour, are respectively measured by

$$Q_1 = Cw(T_1 - t) : Q_2 = Cw(T_2 - t), \text{ nearly}; \quad . \quad . \quad (2)$$

while the efficiency of the heating-surface is measured by the ratio of total heat to absorbed heat; or, if the feed enters at atmospheric temperature, or nearly so, by

$$\frac{Q_1 - Q_2}{Q_1} = \frac{T_1 - T_2}{T_1 - t}, \text{ nearly}. \quad . \quad . \quad . \quad . \quad . \quad (3)$$

The heat utilized, $Cw(T_1 - T_2)$, is also equal to that absorbed and transmitted, qdS:

$$\int qdS = Cw(T_1 - T_2) \text{ and } \frac{S}{Cw} = \int_{T_2}^{T_1} \frac{dT}{q}. \quad . \quad . \quad (4)$$

The value of q has been found to be well represented by equation (4) of article 95, in which $q = \frac{Q}{At}$, and hence $q = \frac{(T_1 - t_c)^2}{a}$; and thus

$$\frac{S}{Cw} = \int_{T_2}^{T_1} \frac{dT}{q} = a\int_{T_2}^{T_1} \frac{dT}{(T-t)^2}. \quad . \quad . \quad . \quad . \quad (5)$$

Assume $(T - t) = x$, then

$$\frac{S}{aCw} = \int_{T_2}^{T_1} \frac{d(T-t)}{(T-t)^2} = -\int_{T_2}^{T_1} x^{-2}dx$$
$$= \Big[-x^{-1}\Big]_{T_2}^{T_1} = \left[\frac{1}{T-t}\right]_{T_2}^{T_1}; \quad . \quad . \quad . \quad . \quad (6)$$

$$\therefore \frac{S}{aCw} = \frac{1}{T_2 - t} - \frac{1}{T_1 - t} = \frac{(T_1 - t) - (T_2 - t)}{(T_1 - t)(T_2 - t)}, \quad . \quad (7)$$

and the efficiency becomes

$$E = \frac{T_1 - T_2}{T_1 - t} = \frac{S}{aCw}(T_2 - t). \quad . \quad . \quad . \quad . \quad (8)$$

Then, since

$$\frac{T_1 - t}{T_2 - t} = \frac{S(T_1 - t)}{aCw} + 1 = \frac{S(T_1 - t) + aCw}{aCw},$$

and

$$\frac{(T_1 - t) - (T_2 - t)}{T_1 - t} = \frac{T_1 - T_2}{T_1 - t},$$

$$E = \frac{T_1 - T_2}{T_1 - t} = \frac{S(T_1 - t)}{S(T_1 - t) + aCw}. \quad . \quad . \quad . \quad (9)$$

If the total heat absorbed per hour be taken as H,

$$H = Cw(T_1 - t); \quad T_1 - t = \frac{H}{Cw}; \quad . \quad . \quad . \quad (10)$$

and a simplified expression,

$$E = \frac{S}{S + \frac{aC^2w^2}{H}}, \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (11)$$

is obtained, in which Cw may be taken as proportional to the weight of air supplied or of fuel burned, and H as proportional to the same quantity. Thus if F is the weight of fuel burned in the given time, on unity of grate-area, the efficiency may be expressed as

$$E = \frac{BS}{S + AF} = \frac{B}{1 + AR}, \quad . \quad . \quad . \quad . \quad (12)$$

which is the formula sought. A and B are constants to be obtained by experiment for the special type of boiler to be considered.

When S and F represent respectively the number of square feet of heating-surface per square foot of grate in any boiler, and the number of pounds of fuel burned as the square foot of grate per hour, and $R = \frac{F}{S}$, the values of A and B, as given by Rankine,* are as follows:

* Steam-engine, p. 294.

Boiler Type.	A.	B.
Class 1. Best convection, chimney draught......	0.5	1.00
" 2. Ordinary " " "	0.5	0.90
" 3. Best " forced "	0.3	1.00
" 4. Ordinary " " "	0.3	0.95

These constants are derived from experience with good fast-burning bituminous coals; for anthracites of good quality the Author has usually found the following values more in accordance with good practice:

Boiler Type.	A.	B.
Class 1....................................	0.5	0.90
" 2....................................	0.5	0.80
" 3....................................	0.3	0.90
" 4....................................	0.3	0.85

When feed-water heaters are used, or superheaters are employed, their surface should be included in the area S. The formula assumes no loss by excess of air-supply. Where such excess is noted or anticipated, it may be allowed for by increasing the value of A in proportion to the square of the total quantity of air supplied. The following table presents values of efficiency for a wide range of practice:

EFFICIENCY OF BOILERS.

R.	Bituminous Coal. Class of Boiler.				Anthracite Coal. Class of Boiler.			
	I.	II.	III.	IV.	I.	II.	III.	IV.
10	0.16	0.15	0.25	0.22	0.14	0.14	0.23	0.20
4	0.33	0.31	0.45	0.43	0.30	0.28	0.40	0.39
2	0.50	0.46	0.62	0.59	0.45	0.50	0.56	0.53
1	0.66	0.61	0.77	0.73	0.60	0.55	0.70	0.66
0.80	0.71	0.65	0.81	0.77	0.64	0.59	0.73	0.69
0.67	0.75	0.69	0.83	0.79	0.67	0.63	0.75	0.72
0.50	0.80	0.73	0.87	0.83	0.72	0.65	0.78	0.75
0.40	0.83	0.76	0.89	0.85	0.75	0.68	0.80	0.77
0.333	0.86	0.80	0.90	0.86	0.77	0.72	0.81	0.78
0.167	0.93	0.85	0.95	0.90	0.84	0.77	0.86	0.81
0.111	0.95	0.87	0.97	0.92	0.86	0.78	0.88	0.83

These values have been found to agree well with practice up to rates of combustion exceeding 50 or 60 pounds per

square foot of grate-surface per hour, beyond which point the efficiency falls off. But agreement can only be expected where the combustion and air-supply are in accordance with the assumptions on which the formula is based.

The problem of the designer of steam-boilers often takes the form: Required to determine the area of heating-surface needed to secure a stated efficiency. In this case the formula above given must be transformed thus:

$$E = \frac{B}{1 + AR} = \frac{B}{1 + \frac{AF}{S}}$$

$$S = \frac{AF}{\frac{B}{E} - 1}; \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (13)$$

$$R = \frac{F}{S} = \frac{A}{\frac{B}{E} - 1}; \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (14)$$

from which expressions, the efficiency aimed at being given, the ratio of heating to grate-surface and the extent of heating-surface may be computed. As will be seen later, the question to what extent efficiency may be economically carried by extending heating-surface is one of the problems arising in designing boilers.

The Area of Cooling-surface demanded to refrigerate liquids, or to condense steam or other vapor, is capable of somewhat similar calculation. Returning to the primary equations of the preceding article, we have

$$\int q dS = Cw(T_1' - T_2'), \quad . \quad . \quad . \quad . \quad . \quad (1)$$

in which we may take T_1 as the measure of the total heat, per unit of weight of the steam entering the condenser or refriger-

ator, and T_2' the temperature of the water of condensation at its exit. As before,

$$S = Cw\int_{T_2}^{T_1}\frac{dT}{tq} = Cw\int_{T_2}^{T_1}\frac{dT}{T-t}; \quad . \quad . \quad . \quad (2)$$

in which t becomes the temperature of the circulating or cooling water, while for such small differences of temperature we may take $q = C(T - t)$, whence

$$\begin{aligned} S &= MCw \log_e \frac{T_1 - t}{T_2 - t} \\ &= N \log_e \frac{T_1 - t}{T_2 - t}; \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (3) \end{aligned}$$

in which expression the value of N may be taken, for ordinary steam-engine condensers, at about 0.04, rising in exceptional case of inefficient apparatus to 0.10, and falling in exceptionally good examples to 0.01, British units being used.

M. Havez has found a similar expression to be practically correct for heating-surfaces, and asserts that we may take the quantity of heat transmitted in either case as decreasing in geometrical progression; while the length of path swept over, measured from the origin, increases in arithmetical progression.* Mr. Williams and M. Petiet both found, in experiments on locomotives, that the evaporation diminished about one half at each step, metre by metre, or yard by yard, from the furnace to the smoke-box end of the tubes.

The efficiency of the heating-surfaces of boilers has been sometimes considerably increased by the expedient of setting pins in the plates in such manner that, projecting into the flue or furnace on the one side and the water-space on the other, they take up heat from the passing gases and conduct it into the midst of the water. A pin may be thus made to absorb and

* *Revue Industrielle*, Mch., 1874.

utilize several times as much heat as could be taken up by the section of the sheet occupied by it. Such "conductor-pins" have often been introduced into marine and other boilers, with very evident improvement in results. Even corrugating a sheet will produce marked advantage in this manner, especially where the direction of the currents is across the lines of corrugation.

99. **The Effect of Incrustation,** and of deposits of various kinds, is to enormously reduce the conducting power of heating-surfaces; so much so, that the power, as well as the economic efficiency of a boiler, may become very greatly reduced below that for which it is rated, and the supply of steam furnished by it may become wholly inadequate to the requirements of the case.

It is estimated that a sixteenth of an inch (0.16 cm.) thickness of hard "scale" on the heating-surface of a boiler will cause a waste of nearly one eighth its efficiency, and the waste increases as the square of its thickness. The boilers of steam-vessels are peculiarly liable to injury from this cause where using salt water, and the introduction of the surface-condenser has been thus brought about as a remedy. Land boilers are subject to incrustation by the carbonate and other salts of lime, and by the deposit of sand or mud mechanically suspended in the feed-water.

It has been estimated that the annual cost of operation of locomotives in limestone districts is increased $750 by deposits of scale.

Professor T. B. Stillman finds that the carbonates are precipitated as such; but that the temperature of the hotter portions of the heating surfaces may drive off the CO_2 and the water of hydration (J. Anal. Chem., Jan. 1890).

CHAPTER V.

HEAT AS ENERGY—ENERGETICS AND THERMODYNAMICS.

100. **Heat as a Form of Energy** is subject to the general laws which govern every form of energy and control all matter in motion, whether that motion be molecular or the movement of masses. Under the title "Energetics" are comprehended all laws affecting bodies, molecules, or atoms in relative motion.

That heat is the motion of the molecules of bodies was first shown by experiment by Benjamin Thompson, Count Rumford, then in the service of the Bavarian Government, who in 1798 presented a paper to the Royal Society of Great Britain, describing his work, and reciting the results and his conclusion that heat is not substance, but a form of energy.

This paper is of very great historical interest, as the now accepted doctrine of the persistence of energy is a generalization which arose out of a series of investigations, the most important of which are those which resulted in the determination of the existence of a definite quantivalent relation between these two forms of energy and a measurement of its value, now known as the "mechanical equivalent of heat." The experiment consisted in the determination of the quantity of heat produced by the boring of a cannon at the arsenal at Munich.

Rumford, after showing that this heat could not have been derived from any of the surrounding objects, or by compression of the materials employed or acted upon, says: "It appears to me extremely difficult, if not impossible, to form any distinct idea of anything capable of being excited and communicated in the manner that heat was excited and communicated in these experiments, except it be motion." * He estimates the heat

* This idea was not by any means original with Rumford. Bacon seems to have had the same idea; and Locke says, explicitly enough: "Heat is a very brisk agitation of the insensible parts of the object, . . . so that what in our sensation is heat, in the object is nothing but motion."

produced by a power which he states could easily be exerted by one horse, and makes it equal to the "combustion of nine wax candles, each three quarters of an inch in diameter," and equivalent to the elevation of "25.68 pounds of ice-cold water" to the boiling-point, or 4784.4 heat-units.* The time was stated at "150 minutes." Taking the actual power of Rumford's Bavarian "one horse" at the most probable figure, 25,000 pounds raised one foot high per minute,† this gives the "mechanical equivalent" of the foot-pound as 783.8 heat-units, differing but 1.5 per cent from the now accepted value.

Had Rumford been able to measure his power and to eliminate all losses of heat by evaporation, radiation, and conduction, to which losses he refers, and to measure the power exerted with accuracy, the result would have been exact. Rumford thus made the experimental discovery of the real nature of heat, proving it to be a form of energy, and, publishing the fact a half-century before the now standard determinations were made, gave us a very close approximation to the value of the heat-equivalent. He also observed that the heat generated was "exactly proportional to the force with which the two surfaces are pressed together, and to the rapidity of the friction," which is a simple statement of equivalence between the quantity of work done, or energy expended, and the quantity of heat produced. This was the first great step toward the formation of a Science of Thermodynamics.

Sir Humphry Davy, a little later (1799), published the details of an experiment which conclusively confirmed these deductions from Rumford's work. He rubbed two pieces of ice together, and found that they were melted by the friction so produced. He thereupon concluded: "It is evident that ice by friction is converted into water. . . . Friction, consequently, does not diminish the capacity of bodies for heat."

* The British heat-unit is the quantity of heat required to heat one pound of water 1° Fahr. from the temperature of maximum density.

† Rankine gives 25,920 foot-pounds per minute—or 432 per second—for the average draught-horse in Great Britain, which is probably too high for Bavaria. The engineer's "horse-power"—33,000 foot-pounds per minute—is far in excess of the average power of even a good draught-horse, which latter is sometimes taken as two thirds the former.

Bacon and Newton, and Hook and Boyle, seem to have anticipated—long before Rumford's time—all later philosophers, in admitting the probable correctness of that modern dynamical, or vibratory, theory of heat which considers it a mode of motion; but Davy, in 1812, for the first time, stated plainly and precisely the real nature of heat, saying: "The immediate cause of the phenomenon of heat, then, is motion, and the laws of its communication are precisely the same as the laws of the communication of motion." The basis of this opinion was the same that had previously been noted by Rumford.

So much having been determined, it became at once evident that the determination of the exact value of the mechanical equivalent of heat was simply a matter of experiment; and during the succeeding generation this determination was made, with greater or less exactness, by several distinguished men. It was also equally evident that the laws governing the new science of thermodynamics could be mathematically expressed.

Fourier had, before the date last given, applied mathematical analysis in the solution of problems relating to the transfer of heat without transformation, and his "Théorie de la Chaleur" contained an exceedingly beautiful treatment of the subject. Sadi Carnot, twelve years later (1824), published his "Réflexions sur la Puissance Motrice du Feu," in which he made a first attempt to express the principles involved in the application of heat to the production of mechanical effect. Starting with the axiom that a body which, having passed through a series of conditions modifying its temperature, is returned to "its primitive physical state as to density, temperature, and molecular constitution," must contain the same quantity of heat which it had contained originally, he shows that the efficiency of heat-engines is to be determined by carrying the working fluid through a complete cycle, beginning and ending with the same set of conditions. Carnot was not a believer in the vibratory theory of heat,* and consequently was led into some errors; but, as will be seen hereafter, the idea

* Documents recently discovered (*Comptes Rendus*, 1878, p. 967) either show this to be an error or prove his later conversion.

just expressed is one of the most important details of a theory of the steam-engine.

Seguin, who has already been mentioned as one of the first to use the fire-tubular boiler for locomotive engines, published in 1839 a work, " Sur l'Influence des Chemins de Fer," in which he gave the requisite data for a rough determination of the value of the mechanical equivalent of heat, although he does not himself deduce that value.

Dr. Mayer of Heilbronn, three years later (1842), published the results of a very ingenious and quite closely approximate calculation of the heat-equivalent, basing his estimate upon the work necessary to compress air, and on the specific heats of the gas, the idea being that the work of compression is the equivalent of the heat generated. Seguin had taken the converse operation, taking the loss of heat of expanding steam as the equivalent of the work done by the steam while expanding. The latter also was the first to point out the fact, afterward experimentally proved by Hirn, that the fluid exhausted from an engine should heat the water of condensation less than would the same fluid when originally taken into the engine.

A Danish engineer, Colding, at about the same time (1843), published the results of experiments made to determine the same quantity; but the best and most extended work, and that which is now almost universally accepted as standard, was done by a British investigator.

Joule commenced the experimental investigations, seeking a measure of the relations of heat and work, which have made him famous, at some time previous to 1843, at which date he published, in the *Philosophical Magazine*, his earliest method. His first determination gave 770 foot-pounds. During the succeeding five or six years Joule repeated his work, adopting a considerable variety of methods, and obtaining very variable results. One method was to determine the heat produced by forcing air through tubes; another, and his usual plan, was to turn a paddle-wheel by a definite power in a known weight of water. He, in 1849, concluded these researches, and announced finally the value 772 foot-pounds as that of the mechanical equivalent of the British heat-unit.

101. **Energetics** treats of modifications of energy under the action of forces, and of its transformation from one mode of manifestation to another, and from one body to another, and within this broader science is comprehended that latest of the minor sciences, of which the heat-engines and especially the steam-engine illustrate the most important applications—*Thermodynamics.* The science of energetics is simply a wider generalization of principles which have been established one at a time, and by philosophers widely separated both geographically and historically, by both space and time, and which have been slowly aggregated to form one after another of the physical sciences, and out of which, as we now are beginning to see, we are slowly evolving wider generalizations, and thus tending toward a condition of scientific knowledge which renders more and more probable the truth of Cicero's declaration: "One eternal and immutable law embraces all things and all times." At the basis of the whole science of energetics lies a principle which was enunciated before Science had a birthplace or a name:

All that exists, whether matter or force, and in whatever form, is indestructible, except by the Infinite Power which has created it.

That matter is indestructible by finite power became admitted as soon as the chemists, led by their great teacher Lavoisier, began to apply the balance, and were thus able to show that in all chemical change there occurs only a modification of form or of combination of elements, and no loss of matter ever takes place. The "persistence" of energy was a later discovery, consequent largely upon the experimental determination of the convertibility of heat-energy into other forms and into mechanical work, for which we are indebted to Rumford and Davy, and to the determination of the quantivalence anticipated by Newton, shown and calculated approximately by Colding and Mayer, and measured with great probable accuracy by Joule.

It is now generally understood that all forms of energy are mutually convertible with a definite quantivalence; and it is not certain that even vital and mental energy do not fall within

the same great generalization. This quantivalence is the basis of the science of energetics.

Experimental investigation and analytical research have together thus created a new science, and the philosophy of the steam-engine has at last been given a complete and well-defined form, enabling the intelligent engineer to comprehend the operation of the machine, to perceive the conditions of efficiency, and to look forward in a well-settled direction for further advances in its improvement and in the increase of its efficiency.

Energy is the capacity of a moving body to overcome resistance offered to its motion;* it is measured either by the product of the mean resistance into the space through which it is overcome, or by the half product of the mass of a free body into the square of its velocity. Kinetic energy is the actual energy of a moving body; potential energy is the measure of the work which a body is capable of doing under certain conditions which, without expending energy, may be made to affect it, as by the breaking of a cord by which a weight is suspended, or by firing a mass of explosive material. The British measure of energy is the foot-pound; the metric measure is the kilogrammetre.

Energy, whether kinetic or potential, may be observable and due to mass-motion; or it may be invisible and due to molecular movements. The energy of a heavenly body or of a coiled spring, and that of heat or of electrical action, are illustrations of the two classes. In Nature we find utilizable potential energy in fuel, in food, in any available head of water, and in available chemical affinities. We find kinetic energy in the motion of the winds and the flow of running water, in the heat-motion of the sun's rays, in heat-currents on the earth, and in many intermittent movements of bodies acted on by applied forces, natural or artificial. The potential energy of fuel and of food has already been seen to have been derived, at an earlier period, from the kinetic energy of the sun's rays, the fuel or the food being thus made a storehouse or reservoir of

* The term "energy" was first used by Dr. Young as the equivalent of the work of a moving body, in his "Lectures on Natural Philosophy" (1807).

energy. It is also seen that the animal system is simply a "mechanism of transmission" for energy, and does not create but simply diverts it to any desired direction of application.

All the available forms of energy can be readily traced back to a common origin in the potential energy of a universe of nebulous substance (chaos), consisting of infinitely diffused matter of immeasurably slight density, whose "energy of position" had been, since the creation, gradually going through a process of transformation into the several forms of kinetic and potential energy above specified, through intermediate methods of action which are usually still in operation, such as the potential energy of chemical affinity, and the kinetic forms of energy seen in solar radiation, the rotation of the earth, and the heat of its interior.

The *measure* of any given quantity of energy, whatever may be its form, is the product of the resistance which it is capable of overcoming into the space through which it can move against that resistance, i.e., by the product RS, or the equivalent expressions $\frac{WV^2}{2g}$ and $\frac{1}{2}MV^2$, in which W is the weight, M the "mass" of matter affected by the motion, V the velocity, and g the dynamic measure of gravity.

The three great laws of energetics are:

(1) The sum total of the energy, active and potential, of the universe is invariable.

(2) The several forms of energy are all interconvertible, and possess a definite quantivalence.

(3) All forms of kinetic energy are tending toward reduction to forms of molecular motion and final dissipation throughout space.

102. Heat-energy and Temperature are closely related and directly proportional, the one to the other.

The investigations of physicists have shown that when p and v are the pressure and volume of unit weight of any gas, and c is the velocity of molecules having the mass m and in number n,

$$pv = \tfrac{1}{3}mnc^2; \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (1)$$

it is also known that

$$pv = RT, \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (2)$$

when $R = \frac{p_0 v_0}{T_0}$, the subscripts denoting that these quantities are taken at the freezing-point of water, and T is the temperature measured from the absolute zero, as hereafter defined ($-461°.2$ F., or $-274°$ C.); hence

$$T \propto c^2, \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (3)$$

and the temperature of any substance, measured on the absolute scale, is proportional to the kinetic energy of the molecules constituting the gas. In other words, as elsewhere stated, temperature is a measure of the intensity of molecular vibration, while quantity of heat, as has been seen, is quantity of molecular energy of vibration.

Thus temperature, as measured on the absolute scale and on the air-thermometer, is directly proportional to the molecular energy of any given mass, and thus, in the case of any confined gas, measures the intensity of pressure on the enclosing walls due to the heat-energy so imprisoned, which quantity is also proportional to the product of this pressure into the volume of the space throughout which it is exerted.

103. Quantitative Measures of Heat-energy, obtained by the various systems of calorimetry, always involve determinations of the magnitudes of factors the product of which give the quantity of molecular energy present. These factors have been seen to be either measures of the mass affected and of molecular velocity, or thermal equivalents. The quantity of heat-energy to be measured is obtained either by multiplying the mass by the square of velocity of vibration, or by the product of the weight into the range of temperature considered and the mean specific heat: these two measures are equivalent. It is by either method made evident that temperature is one factor of a product which is the measure of heat-energy, the

other factor being a measure of the mass of matter acting as the vehicle of that energy.

104. **Heat Transformations** may take place, through the action of physical and chemical forces, into any other known form of energy, and another form of energy may be transmuted into heat. Nearly all physical phenomena, in fact, involve heat-transformation in one form or another, and in a greater or a less degree, under the laws of energetics. According to the first of those laws, such changes must always occur by a definite quantivalence, and when heat disappears in known quantity it is always certain that energy of calculable amount will appear as its equivalent; the reverse is as invariably the case when heat is produced; it always represents and measures an equivalent amount of mechanical, electrical, chemical, or other energy.

105. **Heat and Mechanical Energy** are thus evidently subject to the general laws of transformation of energy, and the transmutation of the one into the other must always be capable of treatment mathematically. The relations of these two forms of energy are thought by the physicist and the engineer as of sufficient importance, and the phenomena involving these relations alone are so often found to demand and to permit independent consideration, that they are taken as the subject of a division of energetics known as the science of *thermodynamics*, and a vast amount of study and research has been given by the ablest mathematical physicists of modern times to the investigation of its laws and their applications, and to the building up of that science.

The conversion of water into steam in the steam-boiler and the utilization of the heat-energy thus made available, or in heated air and other gases, in steam- or other heat-engines, constitute at once the most familiar and the most important of known illustrations of thermodynamic phenomena and their useful application. The process of making steam is one of production of heat by transformation from the potential form of energy through the action of chemical forces, and its storage in sensible form for later use in the steam-engine, where it is changed into equivalent mechanical energy. The pure science

of the steam-engine is thus the science of thermodynamics, the first applications of which are made in the operations carried on in the steam-boiler.

106. **Thermodynamics** is that science which treats solely of the relations of heat and the mechanical form of energy, of the establishment of the laws governing their interconversion, and of the applications of those laws.

The science of thermodynamics is, as has been stated, a branch of the science of energetics, and is the only branch of that science in the domain of the physicist which has been very much studied. This branch of science, which is restricted to the consideration of the relations of heat-energy to mechanical energy, is based upon the great fact determined by Rumford and Joule, and considers the behavior of those fluids which are used in heat-engines as the media through which energy is transferred from the one form to the other. As now accepted, it assumes the correctness of the hypothesis of the dynamic theory of fluids, which supposes their expansive force to be due to the motion of their molecules.

This idea is as old as Lucretius, and was distinctly expressed by Bernouilli, Le Sage and Prévost, and Herapath. Joule recalled attention to this idea in 1848, as explaining the pressure of gases by the impact of their molecules upon the sides of the containing vessels. Helmholtz, ten years later, beautifully developed the mathematics of media composed of moving, frictionless particles; and Clausius has carried on the work still further.

The general conception of a gas, as held to-day, including the vortex-atom theory of Thomson and Rankine, supposes all bodies to consist of small particles called molecules, each of which is a chemical aggregation of its ultimate parts or atoms. These molecules are in a state of continual agitation, which is known as heat-motion. The higher the temperature, the more violent this agitation; the total quantity of motion is measured as *vis viva* by the half-product of the mass into the square of the velocity of molecular movement, or in heat-units by the same product divided by Joule's equivalent. In solids, the range of motion is circumscribed, and change of form cannot

take place. In fluids, the motion of the molecules has become sufficiently violent to enable them to break out of this range, and their motion is then no longer definitely restricted. The science of thermodynamics finds application in every phenomenon in which these various manifestations of heat-energy are accompanied by the performance of work or result from such work.

107. **The First Law of Thermodynamics** is a simple corollary of the first law of energetics; it is enunciated as follows:

Heat-energy and mechanical energy are mutually convertible and have a definite equivalence.

The British thermal unit being equivalent to 772 foot-pounds of work, nearly, and the metric *calorie* to 423.55, or, as usually taken, 424 kilogrammetres.*

The first precise and direct determinations of the mechanical equivalent of the thermal unit were made by Joule, by several methods. He stated the results of his researches relating to the mechanical equivalent of heat as follows:

(1) The heat produced by the friction of bodies, whether solid or liquid, is always proportional to the quantity of work expended.

(2) The quantity required to increase the temperature of a pound of water (weighed *in vacuo* at 55° to 60° Fahr.) by one degree requires for its production the expenditure of a force measured by the fall of 772 pounds from a height of one foot. This quantity is now generally called "Joule's equivalent."

During this series of experiments Joule also deduced the position of the "absolute zero," the point at which heat-motion ceases, and stated it to be about 480° Fahr. below the freezing-point of water, which is not very far from the probably true value, − 493°.2 Fahr. (− 273° C.), as deduced afterward from more precise data.

This first law is that by the application of which we deduce a measure of the quantity of work done whenever a known

* A committee of the British Association reported its value (1878) to be 772.58 foot-pounds, and a later figure is 774, with a limit of error of about two per cent.

amount of heat is transformed; it does not determine how much in any case will be transformed. For example, for any heat-engine we may calculate precisely how much is demanded for the performance of work when it is known how much work is done; but this law affords no means of determining, in any such case, what proportion of the heat-energy sent into the system will be converted into work, or what part will pass through untransformed; and it hence gives no clue to the total quantity of heat called for, or of steam to be made at the boiler, even though all wastes by conduction and radiation be discovered and measured. This clue is given by the second law, which will also enable us to determine the amount of thermodynamically unavoidable loss.

108. The Second Law of Thermodynamics is stated in a great variety of ways by various writers, and is not always clearly enunciated by the best authorities. The following method of statement is adapted especially to present purposes:

In the transfer or the transformation of heat-energy, the total effect produced is directly proportional to the total quantity of heat present and acting.

Thus, if the effect of heat be to produce change of pressure, change of volume, or variation of temperature, the magnitude of that alteration of pressure, of temperature, or of volume will be directly proportional to the quantity of heat concerned in its production. This law is based upon the almost axiomatic proposition, that heat-energy is homogeneous, and equal quantities must invariably be capable of causing equal effects.

Since, in any mass of matter acting as a reservoir or vehicle of heat-energy, the quantity of heat present is proportional to its absolute temperature, it follows, from what has preceded, that the effect produced by any thermal variation in a heated mass is proportional to the absolute temperature at which the action takes place. These propositions and the second law of thermodynamics are expressed algebraically by the equations

$$Q\frac{d}{dQ} = T\frac{d}{dT}, \quad \frac{Q}{T} = \frac{dQ}{dT}; \quad . \quad . \quad . \quad . \quad . \quad (1)$$

in which Q and T are the quantity of heat contained in the body and its absolute temperature. In other words, the product of the absolute temperature by the ratio of variation of any quantity with temperature is equal to the product of the heat acting into the rate of variation of that quantity with the variation of heat.

The quantity of work performed by transformation of heat is measured by

$$dW = Q\frac{d}{dQ}dU = T\frac{d}{dT}dU; \quad . \quad . \quad . \quad . \quad , \qquad (2)$$

which will become known when the law of variation of work, dU, with heat, Q, can be given.

109. The Molecular Constitution of Matter and its physical structure and state determine precisely how heat will affect it, and just how it will behave in the storage, transfer, and transformation of that energy into other forms. All matter consists of particles or molecules, sometimes simple, but usually complex, affected by the forces which become observable under the action of one body upon another. These forces are either attractive, repulsive, or directive. Thus, heat produces a mutual repulsion of molecules, and, if permitted by surrounding masses, the body expands with its reception. Cohesion is an attractive force, as is gravitation, while magnetic and electric forces may be either attractive or repellent; and the polarity seen in the formation of crystals and magnetism gives directive power—the first determining the method of aggregation of approximating molecules, the last the positions assumed by the molecules affected by it. The property of inertia is common to all forms of matter, and is essential to the production of all the phenomena observed in the motion and mutual actions of free bodies.

110. Solids are bodies in which the attractive and directive forces are sufficiently powerful to give stability both of form and of volume. *Liquids* have stability of volume but not of form; while *gases and vapors* have stability neither of form nor of volume, and in them the repellent forces have more intensity

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than the attractive. In gases the latter become insensible, and in the hypothetical "perfect" gas cease to exist. All intermediate degrees of stability exist among the substances known in nature, and no known form of matter can be assigned to either class as a perfect representative of the combination of properties defining it. In passing from one state to another, substances traverse these intermediate conditions. Ice, water, and steam illustrate the three typical classes of matter. In the first the attractive and directive forces give stability of form and strength; in the second, no stability of form exists, but some tenacity or cohesive power remains, which cannot be easily detected in consequence of the freedom of relative motion permitted among its particles when polarity disappears; in the third form of the same substance the fluid must be confined within walls capable of sustaining its outward pressure to keep it from indefinite expansion.

The thermodynamic definition of a perfect gas is found in the equation

$$\frac{pv}{T} = \frac{p_1 v_1}{T_1} = R, \text{ a constant,}$$

the product of pressure and volume always varying with the absolute temperature.

111. **Heat and Matter** have this peculiar relation, that while all other forces which commonly, with that due to the presence of heat, determine to which of the three physical states the latter shall be assigned, are definitely related to the substance, having magnitudes which are functions of volume and of molecular distances, the force introduced with heat, and which is always repellent, is variable, independently of all other conditions, and is, in fact, constantly so varying.

It is the introduction or the removal of heat energy from matter which produces all familiar physical changes of states. When a solid is heated it is expanded against the resisting efforts of all other internal and external forces, and after a time the quantity of heat and the temperature attaining a limit which is perfectly definite for each substance, the directive force becomes

insensible, and the mass becomes liquid. The introduction of heat continuing, the separation of molecules continues until the cohesive force becomes insensible, or at least less than the expansive force of the heat, and the fluid is converted into a vapor; and finally, when the attractive forces disappear entirely, into gas. In this process, internal forces being overcome, internal work is performed, and external forces being overcome, external work is done; while a certain amount of heat, not so expended, is added to the mass as sensible heat, and thus raises its temperature.

Specific Heats measure the quantity of heat absorbed by unit weight of any substance in a change of temperature of one degree, the heat being either all or partly unchanged. It has been already defined and values given in § 91. Thermodynamically considered, it is seen specific heats may measure either heat or work, or both.

112. Sensible and Latent Heats must be carefully distinguished in studying the action of heat on matter. The term "sensible heat" scarcely requires definition; but it may be said that sensible and latent heats represent latent and sensible work; that the former is actual, kinetic, heat-energy, capable of transformation into mechanical energy, or *vis viva* of masses, and into mechanical work; while the latter form is not heat, but is the equivalent of heat transformed to produce a visible effect in the performance of molecular, or internal as well as external, work, and visible alteration of volume and other physical conditions.

It is seen that heat may become "latent" through any transformation which results in a definite and defined physical change, produced by expansion of any substance in consequence of such transmutation into internal and external work; whether it be simple increase of volume or such increase with change of physical state.

113. The Latent Heat of Expansion is a name for that heat which is demanded to produce an increase of volume, as distinguished from that untransformed heat which is absorbed by the substance to produce elevation of temperature. The latent heat of expansion may, by its absorption and transforma-

tion, and the resulting performance of internal and external work, cause no other effect than change of volume, as, e.g., when air is heated; or it may at the same time produce an alteration of the solid to the fluid, or of the liquid to the vaporous state, as in the melting of ice or the boiling of water, in which latter cases, as it happens, no elevation of temperature occurs, all heat received being at once transformed. In the expansion of air, and in other cases in which no such change of state occurs, a part of the heat absorbed remains unchanged, producing elevation of temperature; while another part is transformed into latent heat of expansion.

The specific heat of constant volume, no molecular or other work being done, measures the heat untransformed, and, as sensible heat, producing rise in temperature. The specific heat of constant pressure measures the sum of the sensible and latent heats, when a gas is heated, and no alteration of physical state can occur. It usually is assumed to include both internal and external work, as well as sensible heat, but where used in an unaccustomed sense the conditions of the case are always stated.

114. **The Latent Heats of Fusion and of Vaporization** measure the quantities of heat transformed in these changes of physical state. In the first of these two cases the work done is mainly internal; in the second the internal work performed is much greater, but is not so enormously in excess of the amount of external work done; and the higher the pressure under which vaporization takes place, the larger proportionally the measure of external work and of the heat demanded for its performance. In the case of steam, as will be seen later, at ordinary pressures, the ratio of internal to external work in this change of state is about as ten to one. All this work is performed in the expansion of the mass against resisting molecular attractive forces, unperceivable and incapable of measurement by any ordinary pressure-gauge or physical instrument.

115. **The Distribution of Heat Energy** in thermodynamic operations, and in physical changes produced by it, must be carefully studied, and must be represented in every algebraic expression in the mathematical theory of the subject. As has

been fully shown, the absorption of heat by any substance often involves, and may in any given case involve, three different applications; it may be appropriated to the elevation of temperature; to the expansion of the mass against internal forces, doing internal work; or to the increase of its volume, overcoming external pressures and performing external work. On the other hand, if heat is received from any substance, it may be sensible heat simply transferred without change; or it may be heat produced by transformation out of work through the action of cohesive forces; or it may be heat similarly resulting from the work done by external pressure on the mass during its compression.

Whatever the manner in which heat-energy is transferred or transformed, such phenomena as are observed during the process are subject to the principles which have been stated, and the theory of the process is constructed by the application of the two laws which have been enunciated, and in that manner only. Every algebraic expression representing such a process will be a statement of equality between the total amount of heat-energy entering or leaving the substance, and the sum of the variations of sensible and latent heats in the mass affected.

116. The Application of the First Law leads at once to the construction of the fundamental equations of thermodynamics, and permits the determination of their constants. The first equation to be established is simply a statement, in algebraic language, of the fact that the total quantity of heat absorbed or rejected by any substance during any elementary change must be the sum of the variation of the sensible heat of the mass and of the latent heats. The convertibility of the thermal unit into the mechanical unit of work or energy renders it a matter of indifference which unit is adopted. If Q represent heat measured in thermal and H the same quantity in mechanical units, and if J be taken as the symbol of the mechanical equivalent of heat, and $A = \frac{1}{J}$ the thermal equivalent of the mechanical unit, we may write at once, as the expression of the first law of thermodynamics,

$$dH = JdQ = KdT + dW, \quad . \quad . \quad . \quad . \quad . \quad (1)$$

in which equation K is the dynamical specific heat, or in symbols CJ, the product of the thermally measured specific heat, C, by Joule's equivalent; T the absolute temperature; S the sensible and W the total latent heat, measured in mechanical units.

Hereafter all measurements will be given in mechanical units, unless otherwise stated.

Separating the heat doing the work, W, as distinguished from other heat, into two parts, the one, L, the internal latent heat, the other, U, the latent heat of external work,

$$dH = JdQ = dS + dL + dU, \quad . \quad . \quad . \quad . \quad (2)$$

and making the "internal energy," as it is sometimes called, E, the sum of the sensible heat and internal work,

$$dH = dE + dU. \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (3)$$

Or, otherwise exhibited,

$$dH = \overbrace{dS \quad + \quad \overbrace{dL \quad + \quad dU}^{dW}}$$
$$\underbrace{dS \quad + \quad dL}_{dE} \quad +$$

And these expressions are true for all substances and for all possible cases.

The sensible heat being the product of the specific heat into the range of temperature, and work being always the product of the alteration of volume into the intensities of the mean resistance, the preceding equations may be written:

$$\left.\begin{aligned} dH &= KdT + (p_i + p_e)dv \\ &= KdT + pdv; \end{aligned}\right\} \quad . \quad . \quad . \quad . \quad . \quad (4)$$

when p_i, p_e, and p represent respectively the internal, the external, and the sum of internal and external forces, and v is the volume of the mass, which is assumed to have unity of weight.

When, as here, the two independent variables are temperature and volume,

$$dH = \frac{dH}{dT}dT + \frac{dH}{dv}dv; \quad . \quad . \quad . \quad . \quad . \quad (5)$$

and, from the preceding, we thus find

$$\frac{dH}{dT} = K; \quad \frac{dH}{dv} = p; \quad . \quad . \quad . \quad . \quad . \quad . \quad (6)$$

and the values correspond with the definitions already given.

117. **The Application of the Second Law of Thermodynamics** establishes some important modifications of the equations just derived. Since every effect is proportional to the quantity of heat acting to produce it, and hence to the absolute temperature of the mass,

$$dH = Td\phi = dS + dW; \quad . \quad . \quad . \quad . \quad . \quad (1)$$

in which expression ϕ is that "thermodynamic function" which, being multiplied by the absolute temperature, will give a product measuring the quantity of heat demanded or rejected in the production of the change. Again, since $dW = pdv$, and since, according to the second law, the total pressure, p, must be equal to the product of the absolute temperature at which the change occurs by the rate of variation of pressure with temperature, $\frac{dp}{dT}$,

$$dH = Td\phi = KdT + T\frac{dp}{dT}dT; \quad . \quad . \quad . \quad . \quad (2)$$

and the form and value of the thermodynamic function becomes at once determinable:

$$\phi = \int \frac{dH}{T} = K_v \log_e T + \int \frac{dp}{dT} dv. \quad . \quad . \quad . \quad (3)$$

By a process which need not be here described, and which can be seen in every treatise on thermodynamics, an equation of somewhat similar form, but in which the variables taken are T and p, is obtained, thus:

$$dH = Td\phi = K_p dT - T\frac{dv}{dT}dp; \quad . \quad . \quad . \quad . \quad (4)$$

$$\phi = K_p \log_e T - \int \frac{dv}{dT} dp. \quad . \quad . \quad . \quad . \quad . \quad (5)$$

The fundamental equations of thermodynamics are thus completely established. As here given they are general, and applicable to all substances. In the present work, however, we are only concerned with their application to the operation of thermodynamic changes occurring in water and steam.

118. The Computation of Internal Forces and Work, and of external work, are now easily effected. Notwithstanding the fact, as already stated, that the molecular forces, and the work performed by or against them, are beyond the reach of any physical apparatus and are incapable of direct measurement, it becomes easy to calculate both force and work from measurable data by application of the second law of thermodynamics.

The rate of variation of external pressure and work with temperature, at constant volume, may be determined easily by experiment; this rate, according to the second law, is constant for all temperatures, and hence, being multiplied by the absolute temperature at which the total pressure or the work is to be determined, the product measures that total pressure or work. In symbols, let p, w, and T represent the total pressure and work, and the absolute temperature; then the rates of variation $\frac{dp}{dT}$, $\frac{dw}{dT}$, with temperature may be ascertained by, for

example, noting the change of external pressure, as measured by the steam-gauge, for a change of one degree or other small but exactly measurable range, and taking this ratio of differences, $\frac{\Delta p}{\Delta T}$, as sensibly equal to $\frac{dp}{dT}$. The work-ratio is obtained by multiplying the Δp by the volume and taking this product, $\Delta p \cdot v = \Delta w$, as the numerator in $\frac{\Delta w}{\Delta T} = \frac{dw}{dT}$. Then the total pressure, *internal and external*, must be measured by

$$p = T\frac{dp}{dT}, \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (1)$$

and the total work of expansion from zero

$$w = T\frac{dw}{dT} = T\frac{dp}{dT}v. \quad . \quad . \quad . \quad . \quad . \quad . \quad (2)$$

It thus becomes possible readily to determine the internal and external pressures, the internal and external work, and the latent heats of the vapors, or of any other imperfectly gaseous or non-gaseous substance.

Since the heat rendered latent, in any case, is the equivalent of the work performed by it, the latent heat of vaporization must be exactly equal, dynamically, to the work just measured, and if it be called H for unity of weight,

$$H = T\frac{dw}{dT} = T\frac{dp}{dT}\Delta v, \quad . \quad . \quad . \quad . \quad . \quad (3)$$

when Δv is the increase of volume taking place during the change of physical state. If the value is made known, as is usual, by experiment, and Δv is observed, it becomes easy to obtain

$$\frac{dp}{dT} = \frac{T(v_2 - v_1)}{H}. \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (4)$$

The value of $\frac{dp}{dT}$ is sometimes found to be negative, e.g., in

the case of ice. Professor James Thomson found

$$-\frac{dp}{dT} = 0^\circ.0133 \text{ Fahr.} = 0^\circ.0074 \text{ Cent.}$$

as the amount by which the melting-point of ice is lowered by every increase of one atmosphere of pressure. The latent heat of fusion is similarly measured. The *total heat* of vaporization, as it is called, from a temperature T_1 and *at* a temperature T_2, is the sum of the latent heat converted into work, as just measured, and the sensible heat demanded to raise the temperature from T_1 to T_2.

The latent heat of vaporization per unit of volume is obviously measured by

$$L = \frac{H}{v_2 - v_1} = T\frac{dp}{dT}; \quad . \quad . \quad . \quad . \quad . \quad . \quad (5)$$

and this permits the ready calculation of the heat demanded in supplying any steam, or other vapor, engine with the quantity of fluid required to do any given amount of work, or to drive its piston through any given space, and this without knowing the density of the fluid. The rate of variation of the pressure of the vapor at the boiling-point, with temperature, may be obtained from the tables, or from formulas such as have been given for steam by Regnault, and for that and other vapors by Rankine.* The latter are the most general and usually the most exact; they have the form

$$\log p = A - \frac{B}{T} - \frac{C}{T^2}; \quad . \quad . \quad . \quad . \quad . \quad (6)$$

whence

$$L = T\frac{dp}{dT} = p\left(\frac{B}{T} + \frac{2C}{T^2}\right) \log_e 10. \quad . \quad . \quad . \quad (7)$$

The density of vapor may thus be readily computed from the known value of its latent heat, and much more satisfactorily

* Steam-engine, § 206, Div. III.

and exactly than it can be derived by any known method of experimental determination. The increase of volume of unity of weight must always be

$$v_2 - v_1 = \frac{H}{L}; \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (8)$$

in which, practically, the values of v_1 may usually be neglected. Then the density* is

$$D = \frac{1}{v_1} = \frac{L}{H}. \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (9)$$

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* Tables thus calculated for steam and for ether and other fluids are given by Rankine in his Miscellaneous Papers and in his treatise on the Steam-engine.

CHAPTER VI.

STEAM AND ITS PROPERTIES.

119. **The Production and Use of Steam** involves so important and interesting a series of physical phenomena that they are deserving of special study. The generation of steam, and its supply to the steam-engine or other apparatus in which it finds application, is a process: first, of heating the "feed-water" from the temperature at which it is supplied up to that at which it is vaporized; secondly, the change of its physical state at the latter temperature; thirdly, its expansion into a vapor; and finally, in some cases, the drying and even the superheating of the steam so formed until it assumes the truly gaseous state.

The water supplied to the steam-boiler often comes from rivers or smaller streams, sometimes from springs, occasionally from rain-water cisterns, and, at sea, either from condensers or stills, or from the ocean. Each one of these sources of supply provides water having properties characteristic of its origin, and fitting it, or unfitting it, as the case may be, more or less perfectly for its use in the boiler. The study of the properties of pure water, of its composition and chemical and physical character, and of the nature and effects of the impurities dissolved or mechanically suspended in it, is thus made essential to an intelligent understanding of the problems presented to the engineer who designs, builds, or operates the steam-boiler. The chemistry and physics of water and steam, and of their changes of state and properties, must be studied in connection with the thermodynamics of steam in its application as a vehicle and a reservoir of heat-energy; and with this study must be combined also, and especially, that of the relations of heat and steam to mechanical power as developed by transformation of heat in the steam-engine. This latter division of the subject is commonly reserved for treatises on the steam-engine.

120. The Properties of Water, as noted by the senses, are familiar to all. It occurs universally distributed throughout the world, in earth, air, and sea, in its three forms, ice, water, and vapor, and in its most common and familiar form covers three fourths of the surface of the globe. As ice and snow it permanently covers the arctic regions and the tops of lofty mountains, and as vapor it forms an important constituent of the atmosphere. When pure, it is absolutely free from either taste or smell, and is colorless, except that in very large masses it assumes a beautiful blue tint. In the form of ice it weighs about 55 pounds per cubic foot (0.9 kilog. to the litre, nearly), and has considerable tenacity, while yet capable of flow, with breaking up and "regelation" under pressure.

In the liquid state it still retains considerable cohesive force, but the lack of polarity among its molecules, and its consequent instability of form, so modify its properties that this tenacity cannot be perceived except by the adoption of special expedients directed to that end. Converted into vapor or steam, it assumes all the characteristics of the gases, except that, like other vapors, at temperatures and pressures near the boiling-point it gives evidence of the imperfection of its gaseous state by more rapid variation of pressure with temperature than the laws of the gases would indicate. Heated above the temperature of its boiling-point it rapidly takes on the properties of a true gas, and conforms to the laws of Boyle and Marriotte, and of Charles and Gay-Lussac, and the expression $\frac{PV}{T} =$ constant then becomes sensibly correct.

Water is the most efficient of all known solvents, and under certain conditions dissolves nearly all kinds of matter, even attacking glass and other mineral substances at high temperatures and pressures. Its action on metals is often marked, and is sometimes very serious. It dissolves lead rather freely, so much so that lead-poisoning not infrequently occurs from the presence of that metal in drinking-water held in contact with it. The presence of carbonic acid in observable amount, however, seems essential to the rapid solution of lead, as it invariably is in oxidation. The lead in solder is dissolved more freely

than pure lead alone. Water, especially when containing carbonic acid, dissolves iron and copper rather freely; its presence, either as liquid or as vapor, is absolutely essential to the corrosion of iron; both moisture and carbon dioxide are invariably present when iron "rusts" rapidly.

Bunsen gives the following as the coefficient of absorption by water at the given temperatures, for familiar substances:*

TEMPERATURES.	Cent. 0°. Fahr. 32°.	10° 50°	20° 68°
Hydrogen	0.01930	0.01930	0.01930
Oxygen	0.04114	0.03250	0.02838
Nitrogen	0.02035	0.01607	0.00403
Atmospheric air	0.02471	0.01953	0.01704
Carbon dioxide	1.7967	1.1847	0.9014
" monoxide	0.03287	0.02635	0.02312
Carb. hydrogen, CH_4	0.05449	0.04372	0.03499
" " C_2H_4	0.2563	0.1837	0.1488
Sulph. "	4.3706	3.5858	2.9053
Ammonia	1049.6	812.8	654.0

121. The Composition of Water and its chemistry are well understood in all its technical relations. Cavendish showed its constitution by synthesis in 1781; Humboldt and Gay-Lussac, in 1805, found it to consist of one volume hydrogen and two volumes oxygen; while Berzelius and Dulong determined its proportions by weight, hydrogen one and oxygen eight, i.e.,

	Molecular Weight.	Calculated.	Berzelius and Dulong.	Dumas.
H_2	2	11.111	11.1	11.11
O	16	88.888	88.9	88.89
H_2O	18	100.000	100.0	100.00

Lavoisier made the composition of water one of the bases of his new system.

Water is a neutral compound, exhibiting, when pure, neither acid nor alkaline reaction; but so freely does it dissolve substances with which it is brought in contact, that it is rarely found in nature absolutely free from either acidity or alkalinity. Its presence is essential to nearly all the chemical operations of nature, as well as in the laboratory.

* Methods of Gasometry.

The fluid may be decomposed in either of several ways, as by heat alone, a process of "dissociation" of its elements taking place at between 2000° and 4000° Fahr. (1100° to 2200°C.), or by the voltaic current, and by the action of various metals or metalloids at high temperatures, when the substance employed has a strong affinity for the oxygen, as have carbon, iron, etc.

Water is found wherever hydrogen is burned, in air or oxygen, either alone or in combination with other elements. It enters into combination with many other substances, and as water of crystallization, for example, often influences the character of the compound to a very important degree.

122. **The Sources and Purity of Water** demand careful attention from the engineer proposing to use it in the production of steam; since the presence of any foreign matter is always productive of some and sometimes of serious difficulties, and even of dangers. Rain-water is the purest of all natural waters; but even rain-water contains all such gaseous substances in solution as may have been dissolved in its fall through the atmosphere, and such minute quantities of organic and other solid matter as are found floating in the air. The volume of dissolved gas is usually about 25 parts in 1000 of water. As oxygen dissolves more freely than nitrogen, their proportions in solution differ from those of the atmosphere, averaging not far from one third oxygen and two thirds nitrogen.

Spring-waters hold in solution every soluble element or compound found in the rocks and soils through which they flow. The purest of them are those "soft" waters rising from granitic formations; those of limestone districts contain, often, considerable quantities of lime, and are very "hard." Spring-waters are often so heavily charged with dissolved substances as to be useless for domestic or manufacturing purposes. Good spring-water is, however, often found "fresh" and pure, and such water should always be sought for use as "feed-water" for steam-boilers.

River-water is usually purer than spring-waters, even although largely consisting of such waters. The dilution of the stream by surface-water, the precipitation of lime and other salts held in solution only by carbonic acid, which is set free on exposure to

the atmosphere, and the purifying influences of the atmosphere, all together may very greatly reduce the proportion of impurity. River-water is apt to contain more organic matter than does spring-water; this is sometimes, though rarely, dangerous in boilers. It is liable to contain large quantities of sand, clay, or other kind of soil, mechanically suspended; but this can usually be removed sufficiently well by filtering.

A water carrying a considerable amount of the carbonate of lime and other alkalies in solution, and used in the boilers of locomotives in the Mississippi valley, deposited a scale having the following analysis:

Iron peroxide	5.700	per cent.
Silica	2.960	"
Potassa	5.131	"
Alumina	.320	"
Soda	2.137	"
Sulphuric acid	.006	"
Lime	24.760	"
Magnesia	8.294	"
Carbonic acid	41.060	"

The effect was to produce some leakage and marked loss of economy. This may be taken as a fair sample of the incrustation to be expected in limestone districts.

123. Sea-water is a "mineral water," strongly saline, considerably chlorinated, and slightly alkaline. The composition of the water of the ocean differs very slightly in different localities. It contains about $\frac{1}{32}$ of its own weight of salts, mainly common salt, with various other chlorides and bromides, and some gases.

The following analysis was made by Von Bibra:

Sodium chloride	1671.34
Magnesium chloride	199.66
Sodium bromide	31.16
Potass. sulphate	108.46
Magnes. "	34.99
Calcium "	93.30
Total in 1 U. S. gallon	2138.91 grs.,

or 3.569 per cent, by weight.

Forschammer finds for each 100 parts chlorine:

	SO_4	Mg	Ca	Total.
Maximum............	14.51	6.768	2.257	181.40
Mean...............	14.26	6.642	2.114	181.10
Minimum............	13.98	6.570	2.050	180.60

In some inland seas, as the Great Salt Lake and the Dead Sea, the proportion of saline matter is enormously greater. Herapath found the latter to contain 19.73 per cent solid matter, of which one half was common salt, and one third magnesium chloride; the next largest constituents were the calcium and potassium chlorides and sodium bromide.

Deposits from sea-water, and from any other water containing solid matter either in solution or suspended, will always occur on evaporating the water; and these deposits form the incrustation and sediment which endanger the steam-boiler and reduce the efficiency of its heating-surfaces. They are prevented at sea, usually, by the adoption of the surface-condenser, or by the process of "pumping and blowing" where the jet-condenser is employed, and when the sea-water is thus unavoidably used in the boiler. This will be referred to in describing the operation and management of the marine steam-boiler.

The salts in sea-water are not precipitated at the boiling-point; but, in a concentrated solution at 217° Fahr. (102° Cent.), sulphate of lime begins to come down, and at the temperatures customarily met with in marine steam-boilers it is all deposited. A saturated solution of common salt is obtained at a temperature of about 230° Fahr. (110° Cent.) and at one tenth the volume of the sea-water, the salt having increased in its percentage from 3 to 30. A cubic foot of sea-water weighs about 64 pounds, or $\frac{36}{35}$ that of fresh water, the one measuring 35 and the other 36 cubic feet to the ton, nearly. The boiling-point of salt water rises about 1°.2 Fahr. (0°.7 Cent.) for every 3 per cent of salt added up to the point of saturation. (See § 126.)

The character of the water in a marine steam-boiler, after long working, and with the usual moderate concentration, is shown by analyses made for the Author by Dr. Albert R. Leeds, the report on which was as follows.

EXAMINATION OF WATERS FROM A MARINE BOILER, WITH REFERENCE TO CAUSES OF RAPID CORROSION OF HEATING-SURFACES.

Samples.

1. Forward end of boiler; 2, after end of boiler; 3, hot well.

Preliminary Instructions and Analyses.

The instructions were to examine for organic acids and copper.

All the organic acids that could possibly occur under the circumstances were looked for in Nos. 1, 2, and 3. None present.

Of copper, none was found except in No. 1, and then only a *trace* when the examination was repeated on a larger quantity of liquid. If the quantity of water at my disposal had not been so limited, a similar examination of No. 2 might have revealed a trace of copper in it also.

These results being inadequate to explain the causes of corrosion, the following analyses were required:

ANALYSES OF THREE SAMPLES.

Amount of Solid Matter in Waters.

1.	100 cubic cent.	4.562	grammes.
	(Corresponding to about 6.1 oz. in 1 U. S. gallon.)		
2.	100 cubic cent. contained	4.8386	"
3.	100 " " "	0.2680	"

Loss by Ignition.

These residues were obtained by drying at 110° C. On ignition, water was given off, and a partial decomposition, attended with loss of chlorine, ensued. But unlike many samples of water, the loss by ignition in these cases is *not* to be attributed to organic matter present.

No. 1 lost	9.43	per cent.
" 2 "	6.01	"
" 3 "	15.11	"

Results of Qualitative Analysis.

	1.	2.	3.
Organic acids	None.	None.	None.
Chlorine	Present.	Present.	Present.
Ammonia	None.	None.	None.
Lime	None.	Trace.	None.
Magnesia	Abundant.	Abundant.	Abundant.
Oxide of iron	None.	None.	None.
Copper	Trace.	None.	None.
Sulphuric acid	Present.	Present.	Present.
Sodium	Large.	Large.	Large.
Bromine, } not tested for.			
Iodine, }			

The most striking feature is the large amounts of the chlorides and sulphates of the alkalies and magnesium—more especially the magnesium salts.

Specific Gravities and other Properties.

Specific gravity of No. 1	1.0300	15° C.
" " " 2	1.0309	"
" " " 3	1.0030	"

1 was slightly turbid from suspended matter, but colorless; 2, turbid, and of a slightly pinkish color; 3, colorless and clear.

It will be noticed that the specific gravities of Nos. 1 and 2 are somewhat greater than the average specific gravity of sea-water, which is 1.027.

Corrosive Properties of the Water.

Ex. 1.—A galvanic pair was made of a plate of copper and one of iron, separated below but in contact above the liquid. On immersion into water No. 1 hydrated sesquioxide of iron was rapidly formed. No notable deposit of copper could be detected on the iron plate, and no trace of copper in the liquid. If the minute trace of copper was precipitated out, the coating was too slight to be visible.

Ex. 2.—A sheet of iron alone was immersed in the water No. 1 at the boiling-point. Oxide of iron was formed, but in much less quantity than in Ex. 1.

Ex. 3.—A galvanic pair, as in Ex. 1, was put in the circuit of a galvanometer. On making contact a large deflection took place, showing high tension, the needle coming to rest with a permanent deflection of 3°. At the same time oxidation of the iron went on rapidly.

Conclusions.

That water having a composition as above given, and without organic acids, is capable of producing corrosion of the iron; that such water, when it is the exciting fluid in a galvanic combination, one element of which is iron, the other copper, produces a galvanic current of notable quantity and intensity. Under such circumstances corrosion of the iron takes place more rapidly than when iron alone is in contact with the liquid.

124. **Technical Uses** and manufacturing operations commonly require the purest possible water. In the steam-boiler, especially, where all the water evaporated necessarily leaves behind every particle of solid matter held in solution at its introduction, purity of the fluid is of great importance. Half a ton of lime "scale" has been taken from the boiler of a locomotive, and the Author has seen several tons of salt and scale in a large marine boiler which had been ruined by its presence, and the consequent destruction of its furnace and furnace-flues by overheating and oxidation. Boiler explosions have often been caused by such incrustations. The prevention and removal of scale is a matter of serious importance in steam-boiler management, and will be considered later. It may be stated here that various chemical reagents are relied upon to produce a removable and comparatively safe form of salt-deposit, and heating and filtration of the water before it enters the boiler are usually the best preventives.

Filtration by means of filter-beds for large volumes of water, and by filtering apparatus of various kinds, may always be relied upon to remove the undissolved solid matter. Filtration is often combined with heating and sometimes with chemical treatment in the purification of water.

The temperatures at which calcareous matters are precipitated in ordinary boiler waters are as follows:

Carbonates of lime, between............	176° and 248° Fahr. (80° to 120° C.)
Sulphates of lime, between.............	284° and 424° Fahr. (140° to 218° C.)
Chlorides of magnesium, between.......	212° and 257° Fahr. (100° to 124° C.)
Chlorides of sodium, between...........	324° and 364° Fahr. (160° to 184° C.)

The presence of the chlorides causes retardation of the deposition of the sulphate to a very considerable degree.

125. **Water-analysis** is often resorted to by the engineer to determine the proportion of scale-forming constituents in water to be used in steam-boilers. The determination of the specific gravity is sometimes a first step; but the variations from that of pure water are usually too slight to be observable. Where it is taken it is best done by weighing on the chemist's balance. Color is observed by filling a long glass tube, capping the ends with plate glass, and looking through it at a white background, beside a tube similarly prepared containing pure water. The smell and taste are noted, both cold and warm, and the water is tested with litmus-paper to detect any acidity or alkalinity; should the paper turn blue, and again lose the color on exposure to the air, ammonia is indicated.

The total dissolved solid matter contained is ascertained by evaporating to dryness, after filtration, and weighing the deposit. The final drying is usually completed in a steam-bath at the boiling-point, 212° F. (100° C.). The weight of fixed mineral contents is then estimated by igniting until all organic matter is decomposed and its carbon burned away, and the loss of weight noted. The suspended matter may be weighed from the filters, or may be obtained by allowing it to settle in a still tank or large bottle until the water is perfectly clear, decanting and weighing after drying.

The "hardness" of water is gauged by several methods, of which Clark's is one of the best. It depends upon the fact that when water is pure it froths when shaken up with an alcoholic solution of soap; while if mineral salts are present it remains free from "suds" until a considerably increased amount of soap is introduced. The quantity of soap required to produce observable frothing is a fairly good gauge of the hardness of the water. This hardness is measured in "degrees," each of which is equal to 0.01 gramme of calcic carbonate, or its equivalent,

to the litre, i.e., one part in 100,000. The standard solution is made by dissolving white curd-soap in alcohol of 0.92 s. g., until 100 cubic centimetres will make a froth with an equal quantity of water of 20° hardness. This is preserved in glass-stoppered bottles, and sometimes diluted to make other standard solutions. The presence of a considerable proportion of magnesian salts causes the indication of this test to be defective, giving too low a figure for the hardness.

Carbonates precipitated by boiling are dried and weighed. Organic matter is calcined and so determined roughly, or may be measured by reaction with potassic permanganate. The amounts of the several solid constituents are customarily expressed as parts in 1,000,000, by weight, of the water; sometimes as grammes in the litre, and also as grains to the gallon: the last may be reduced from the next preceding by multiplying grammes per litre by 0.07; they can be converted into degrees on Clark's scale by multiplying by 0.7. Cubic centimetres per litre may be converted into grains per gallon by dividing by 3.738.

126. The Purification of Water is often essential both for sanitary and commercial purposes. The first and simplest process of purification of water containing dissolved substances is distillation. The liquid is boiled in closed vessels, and the steam conducted into a condenser, and there restored to the liquid state by cooling. All salts and solid matters are left behind in the evaporating vessel, and the distilled fluid is absolutely pure if the process is conducted in vessels of insoluble metal or of glass. In many cases the lime salts are precipitated by simple heating without vaporization, the solid precipitate coating the surfaces of the heater or the stone or other masses with which it is sometimes partly filled. The addition of common washing soda is better than the use of the nostrums sold as "scale preventives." The safest course is always to have the water analyzed, and thus to ascertain the best method of treatment. Saccharine and amylaceous matters and extractive substances are useful in preventing the deposition of lime and magnesian carbonates in a hard scale, and barium chloride is effective in a similar manner, where the water contains calcic

sulphate. Water may be purified of its lime salts, the lime being held in solution as a bicarbonate, by the addition of lime-water, which takes a part of the carbonic acid and causes complete precipitation. This process has been used in the purification of feed-water for use in steam-boilers; but the great quantity of water used generally makes it a somewhat expensive system. M. E. Asselin recommends the use of glycerine to prevent incrustation in steam-boilers.

Glycerine soluble in water in every proportion increases the solubility of combinations of lime, and especially of the sulphate; it appears besides to form with these combinations soluble compounds. When the quantity of lime becomes so great that it can no longer be dissolved, nor form with the glycerine soluble combinations, it is deposited in a gelatinous substance, which never adheres to the surface of the iron plates. Moreover, the gelatinous substances thus formed are not carried with the steam into the cylinder of the engine.

M. Asselin advises the employment of one pound of glycerine for every 300 or 400 pounds of coal burnt, fifteen days' supply being introduced at once. Glycerine combines with all the salts, and leaves the plates perfectly clean.

Filtration, as has been already stated, is the process by which all mechanically-suspended matter is removed from water (§ 124).

127. The Physical Characteristics of Water, when pure, are the following: Its density is about 770 times that of air, and is a maximum at about $39^{\circ}.2$ Fahr. (4° Cent.), with exceedingly slight variation through ordinary ranges of temperature. This is taken as unity, and as a standard for all densimetric determinations with solids or liquids. Water is perfectly elastic with a very great modulus; at low temperatures the compressibility increasing with temperature, and decreasing with its solution of salts. Grassi, Amaury and Descamps, and Cailletet, all find the coefficient of compressibility at mean atmospheric temperature to be 0.000045 to 0.000046. At the freezing-point it becomes 0.00005.

On the application of heat, water expands from unity to 1.043, in passing from the freezing to the boiling point. It has a very high heat-capacity, which is taken as unity in comparing

specific heats of other substances. It is an almost perfect non-conductor of heat, and only transfers heat readily by convection. Its conductivity in absolute measure is about 0.002. On reducing its temperature to 32° F. (0° C.) water freezes, and the ice produced has a specific gravity, when solid and pure, of 0.92, and floats on the surface of water at the same temperature. The expansion observed at freezing takes place with immense force, and often bursts water-pipes when they are frozen up. The boiling-point of water, under atmospheric pressure, is at 212° Fahr. (100° Cent.), and very variable, as shown later, with change of pressure. The boiling-point also rises with the increase of density by the solution of other substances.

One cubic foot of water weighs 62.425 pounds at maximum density, or nearly 1000 ounces (62.5 pounds). The cubic metre weighs 1000 kilogrammes. One atmosphere counterbalances a column of water 33.95 feet (10.35 m.) high.

The following table gives the volume and weight of distilled water at various temperatures:

Temperature.	Ratio of volume to that of equal weight at maximum density.	Weight of a cubic foot.	Temperature.	Ratio of volume to that of equal weight at maximum density.	Weight of a cubic foot.	Temperature.	Ratio of volume to that of equal weight at maximum density.	Weight of a cubic foot.
Fahr.		*Lbs.*	*Fahr.*		*Lbs.*	*Fahr.*		*Lbs.*
32.°	1.000129	62.417	210.°	1.04226	59.894	390.°	1.15538	54.030
39.1	1.000000	62.425	212.	1.04312	59.707	400.	1.16366	53.635
40.	1.000004	62.423	220.	1.04668	59.641	410.	1.17218	53.255
50.	1.000253	62.409	230.	1.05142	59.372	420.	1.18090	52.862
60.	1.000929	62.367	240.	1.05633	59.096	430.	1.18982	52.466
70.	1.001981	62.302	250.	1.06144	58.812	440.	1.19898	52.065
80.	1.00332	62.218	260.	1.06679	58.517	450.	1.20833	51.662
90.	1.00492	62.119	270.	1.07233	58.214	460.	1.21790	51.256
100.	1.00686	62.000	280.	1.07809	57.903	470.	1.22767	50.848
110.	1.00902	61.867	290.	1.08405	57.585	480.	1.23766	50.438
120.	1.01143	61.720	300.	1.09023	57.259	490.	1.24785	50.026
130.	1.01411	61.556	310.	1.09661	56.925	500.	1.25828	49.611
140.	1.01690	61.388	320.	1.10323	56.584	510.	1.26892	49.195
150.	1.01995	61.204	330.	1.11005	56.236	520.	1.27975	48.778
160.	1.02324	61.007	340.	1.11706	55.883	530.	1.29080	48.360
170.	1.02671	60.801	350.	1.12431	55.523	540.	1.30204	47.941
180.	1.03033	60.587	360.	1.13175	55.158	550.	1.31354	47.521
190.	1.03411	60.366	370.	1.13942	54.787			
200.	1.03807	60.136	380.	1.14729	54.411			

128. Changes of Physical State from ice to water, or from water to steam, or the reverse, are brought about by change of temperature and pressure. The heating of ice from any temperature below freezing up to its melting-point causes an expansion of the mass and the conversion of a part of the heat supplied in the performance of the work of separation of molecules, and in less degree that of expansion of the mass against atmospheric pressure. At the melting-point rise in temperature ceases, and all heat received is transformed into the work of "disgregation," as Clausius has called it, until such a separation of molecules has been effected that stability of form is lost with the vanishing of the visible effect of the polarizing forces, and the mass becomes liquid. This change of physical condition having been effected, the addition of heat again causes rise in temperature, until a second halt takes place at the boiling-point and a second change of state produces vaporization. Above this latter point, the boiling-point, the absorption of heat once more causes increase of temperature. There are thus two marked phenomena to be noted in applying heat to this substance, and at every stage the heat-supply is to be observed and compared with the amount of heating and of work done internally and externally; the two quantities, that received and the sum of these expenditures, will always be found to balance.

129. The "Critical Point" is that at which the fluid is indifferently liquid or vapor at the same temperature and the same pressure. As the pressure increases and temperature rises, the quantity of heat rendered "latent" by conversion into the work of vaporization decreases, and with probably every fluid a point is finally reached at which a critical set of conditions is attained, the latent heat of expansion becoming zero, and the body exhibiting the properties of the liquid or of the vapor accordingly as it is above or below this point on the thermometric and pressure scales. M. Cagniard de la Tour in 1822 first observed that, on raising the temperature of a confined fluid, partly liquid and partly gaseous, a point might be reached at which the whole mass suddenly became homogeneous in appearance; and he supposed the action that of sudden gasification. Fara-

day found, a year later, as he stated it, that, above a certain temperature, definite for each case, no amount of pressure would cause liquefaction of a vapor; and Dr. Andrews, who studied the phenomenon very carefully, finally concluded that at this "critical" point the properties of the two forms of matter blended—that the one passes into the other without interruption of continuity; these physical states being thus found to be separate forms of the same condition of matter. M. de la Tour reported several critical temperatures and pressures, thus:

	Temperature.		Pressure Atmos.
Ether	369°.5 F.	187°.5 C.	37.5
Alcohol	497°.5 F.	258°.5 C.	119.0
Carbon disulphide	504°.5 F.	262°.5 C.	66.5
Water	773°.0 F.	411°.7 C.	?

At a temperature and pressure near that above given water dissolved glass. Steam in this condition, or of higher temperature and pressure, being worked in the steam-engine, would superheat while expanding; at ordinary temperatures and pressures, and below this critical state, it partially condenses while expanding behind a piston, and thus performing work—a fact predicted by Rankine and Clausius in 1849, before its experimental discovery.

Isothermal lines of temperatures considerably above those of the critical points for the various pressures are sensibly hyperbolic; but as these critical pressures and temperatures are approached the curve becomes distorted, and gives a combination of nearly straight lines up to the boiling-point, a perfectly straight line of constant pressure and variable volume during vaporization, and finally it is hyperbolic when the gaseous state is attained, as in the vaporization of water.

Fig. 65 exhibits a set of isothermals for carbon dioxide, as drawn from Dr. Andrews' data. The dotted lines indicating the probable form, as suggested by Professor James Thomson,* of portions not obtainable from those data, are by him given the Author, as shown. Each curve relates to one temperature, and

* Rept. Brit. Assoc. 1871.

pressures are represented by the horizontal ordinates, and corresponding volumes of mass of carbonic acid constant throughout all the curves are represented by the vertical ordinates.

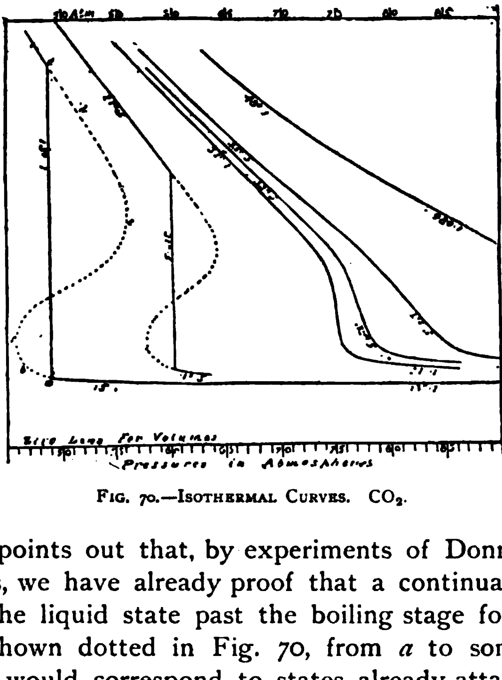

Fig. 70.—Isothermal Curves. CO_2.

Thomson points out that, by experiments of Donny, Dufour, and others, we have already proof that a continuation of the curve for the liquid state past the boiling stage for some distance, as shown dotted in Fig. 70, from *a* to some point *b* towards *f*, would correspond to states already attained. The overhanging part of the curve from *c* to *f* may represent a state in which there would be unstable equilibrium; and thus, although the curve there appears to have some important theoretical significance, yet the states represented by its various points would be unattainable throughout any ordinary mass of the fluid. It seems to represent conditions of coexistent temperature, pressure, and volume, in which, if all parts of a mass of fluid were placed, it would be in equilibrium, but out of which it would be led to rush, partly into the rarer state of gas, and partly into the denser state of liquid, by the slightest inequality of temperature or of density in any part relatively to other parts. Above this point the fluid, as shown by the hy-

perbolic form of curve, is thoroughly *gaseous ;* below that point it may be called vapor.

130. **The Spheroidal State** of water is that condition observed when water lies in contact with highly heated metal surfaces. When so situated, a liquid does not wet the metal, but is supported quite out of contact with it by a cushion of rapidly forming vapor. A very small mass assumes the form of a drop, a larger quantity that of a sheet of liquid of continually changing outline. The supporting "Crookes's layer," as it is sometimes called, consists of particles constantly bounding and rebounding between the adjacent surfaces of fluid and metal, and gradually finding their way out of that capillary space as their places are taken by newly formed particles of vapor. Ether and bromine can be similarly supported on the surface of heated water, and ice can be produced in a red-hot crucible without contact. On cooling the metal, a temperature is finally reached (356° F., 180° C.) at which contact occurs, and an explosion often follows from the sudden and considerably increased evolution of steam.

This, which is named, from its discoverer, Leidenfrost's phenomenon, or, otherwise, the "caloric paradox," has been very carefully studied, especially by Boutigny. The temperature of the spheroid of liquid is found always to be lower than its boiling-point; contact never exists, during the continuance of the phenomenon, between metal and liquid. This action is promoted by any conditions which tend to prevent actual contact and wetting of the metal by the liquid, a fact having important bearing on the special danger of certain forms of oily or of pulverulent scale in steam-boilers. This interesting and important action is illustrated in the impunity with which the hand may sometimes be dipped in molten metal, the moisture on its surfaces protecting it from contact and injury.

Superheated water or other liquid may be sometimes obtained by careful management, as in the experiments of Donny, Dufour, and others. When water is deprived of air and of all impurities it may be raised to a temperature considerably exceeding the boiling-point. The smaller the mass, the higher the temperature attainable. M. Donny raised water in a closed

glass tube to 248° F. (138° C.), when explosive ebullition occurred, and the thermometer dropped to 212° F. (100° C.). Minute drops (1 to 3 mm. or 0.04 to 0.12 in. in diameter) attained 346° F. (175° C.), when suspended in a mixture of oils of its own density, a temperature at which the tension of steam in contact with its water is, under normal conditions, between 8½ and 9 atmospheres. Water in glass vessels always boils, if pure, at a temperature slightly exceeding the ordinary boiling-point. Larger masses or impure water are not easily superheated. M. Dufour found that water retains the liquid state more persistently when the temperature is constant and pressure is made the variable than when the contrary conditions are arranged. MM. Donny, Dufour, and others have suggested that this phenomenon may be a frequent cause of a class of boiler-explosions known as "fulminating," in consequence of their violence; and Mr. Radley, an English engineer, reported * having actually superheated the water in small steam-boilers 27° F. (15° C.) above the normal boiling-point for the pressure at which they were working. On the other hand, Mons. Hirsch, the well-known French engineer and author, reports to the Commission Centrale des Machines à Vapeur the results of experiments of a committee on the production of the superheated condition in the water of steam-boilers, in which, studying the history of such phenomena so far as they are recorded, and conducting a somewhat extended series of experiments, the conclusion was finally reached that there is no evidence, up to the present time, that boiler explosions may be caused by the conditions studied, or that such conditions ever arise in practice. If they occur at all, it is only in extremely rare instances, and as a consequence of a coincidence of circumstances seldom to be observed, and which are neither well understood nor well defined. The use of the thermometer is advised to determine the facts bearing upon this question. The commission to which the report is made approve and adopt these conclusions.

131. **Vaporization** of water or other liquid has been seen to be a process of conversion of sensible heat-energy into the so-

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* *Lond. Mining Journal*, June 28, 1856; *Scientific American*, Aug. 2, 1856.

called latent form by transformation into work in the separation of molecules, and consequent change of state of the fluid. This change has been found to be invariably produced at a temperature fixed for every pressure under normal conditions, and to demand a certain exact and determinable quantity of heat. The vapor thus formed, so long as it is in contact with the liquid from which it issued, retains the precise temperature of ebullition, and in this condition the steam is said to be saturated. If it contains no unevaporated moisture, it is said to be dry and saturated. It is capable of being superheated by isolation and further addition of heat, and then rapidly assumes more or less perfectly the gaseous state. M. Hirn found that this state is sensibly reached when the superheating amounts to anything above 16° F. (9° C.). The fluid is known in this condition as "steam-gas."

The specific heat of superheated steam is 0.48, equivalent to 371 foot-pounds, at constant pressure, and is 0.37 (286 foot-pounds) at constant volume. The quantity of heat doing internal work here becomes insensible. The processes of conversion of the liquid into vapor and of the vapor into gas are seen to be, physically, very similar.

132. The Thermal and Thermodynamic Phenomena attending the production, storage, and transfer of heat-energy through the vaporization of steam are evidently in some sense identical phenomena. The communication of heat to a mass of water enclosed in a steam-boiler results in the raising of its temperature, the expansion of the mass, the performance of work, and the conversion of heat-energy in the doing of that work. The boiling-point is simply a point in the process at which the proportion in which the heat received is distributed to its several purposes is altered, and the superheating of steam is the result of passing another critical period in the process. The principles involved and these phenomena have been already fully explained, and it is only necessary here to apply those principles and the data obtained by experiment to the special case in hand—the production and use of steam. It is perfectly easy to determine just how much sensible heat is employed, untransformed, in raising the temperature of water or

steam; how much is transformed in producing expansion, and how much as the latent heat of change of state.

133. Internal Pressure and Work, in the case of steam, will illustrate the general case of thermodynamic change as already presented. The magnitude of the molecular resistance to expansion is well ascertained, and the quantity of work done in overcoming them in the process of making steam is as easily determinable. As has been shown, the quantity of heat becoming latent is the equivalent of this internal work, and the sum of the latent and the sensible heat absorbed is the total heat demanded to produce the change. Both may be determined by the processes which have been described in the earlier chapters.

134. The Computation of Internal Work or of internal pressure has been seen to be based on the principle expressed in the statement of the second law of thermodynamics.

The total pressure, internal and external, at any temperature, T, is always

$$p = T\frac{dp}{dT}. \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (1)$$

The rate of variation, $\frac{dp}{dT}$, of pressure as a function of temperature is determined experimentally, and the value of this expression may be obtained from the expressions already given, or from the tables of Regnault. The work done is the product of their total pressure, p, into the alteration of volume, Δv, or

$$W = p\Delta v = T\frac{dp}{dT}\Delta v. \quad . \quad . \quad . \quad . \quad . \quad . \quad (2)$$

Internal pressure and work are computed by deducting external pressure and work from these totals.

Clausius thus obtained the following values of p for steam of the pressures given, all in millimetres of mercury, of which 760 measure one atmosphere of pressure:

TOTAL PRESSURES OF STEAM.

Centigrade.		External Pressure.		Ratio $\frac{dp}{dT}$.	Total Pressure $p = T\frac{dp}{dT}$.	Ratio $\frac{p}{p_e}$.
t.	T.	p_e	At.			
100°	374°	760	1	27.200	10146	13.3
120	394	1520	2	48.595	19150	12.6
134	408	2280	3	67.020	27277	11.9
144	418	3040	4	84.345	35172	11.5
152	426	3800	5	100.375	42659	11.2
159	433	4560	6	116.085	50149	11.0
166	440	5320	7	133.445	58502	10.8
171	445	6080	8	146.910	65228	10.7
176	450	6840	9	161.27	72410	10.6
180	454	7600	10	173.425	78561	10.4
199	473	11400	15	239.57	113077	9.9

It is seen that the rate of variation of pressure with the temperature of steam continually increases as pressures and temperatures rise, and that the proportion of internal to external work and pressure continually diminishes; but that the latter ratio is large, about ten to one, for the whole range of pressures familiar in standard practice.

135. **The Specific Volume** of steam, or the volume of unity of weight, and its reciprocal, the density, have been seen to be capable of easy computation when the latent heat of vaporization at the given temperature is known; since this latent heat measures the work done while the force resisting it is calculable as above. From the expressions already given

$$H = T\frac{dp}{dT}\Delta v; \quad \Delta v = \frac{H}{T} \div \frac{dp}{dT};$$

we thus obtain very exact values.

Clausius thus obtains the following values, and compares them with the somewhat uncertain figures of Fairbairn and Tate, derived experimentally. Metric measures are employed.

t.	T.	Δv Calculated.	Δv. By Experiment.
117.17	391.17	0.947	0.941
124.17	398.17	0.769	0.758
128.41	402.41	0.681	0.648
137.46	411.46	0.530	0.514
144.74	418.74	0.437	0.432

Quite accurate results can also be obtained by taking the density of steam as 0.622; that of air at the same values of t and p being unity. (See p. 282.)

The volume of water increases with temperature, from the temperature of maximum density, more and more rapidly as the heat is increased. The following are the values as given by M. Kopp, who experimentally determined them, and as corrected by Mr. Porter to make the curve exhibiting the data perfectly smooth:

Temperature.		Volumes as per	
Cent.	Fahr.	Kopp.	Porter.
4°	39°.1	1.00000	1.00000
5	41 .0	1.00001	1.00001
10	50 .0	1.00025	1.00025
20	68 .0	1.00169	1.00171
30	86 .0	1.00423	1.00425
40	104 .0	1.00768	1.00767
50	122 .0	1.01190	1.01186
60	140 .0	1.01672	1.01678
70	158 .0	1.02238	1.02241
80	176 .0	1.02871	1.02872
90	194 .0	1.03553	1.03570
100	212 .0	1.04312	1.04332

136. Temperature, Pressures, and Volumes of Steam are related by natural law quite as definitely as those governing these relations for the gases; but algebraic expressions of those laws are not yet obtained, except empirically. There have been numerous formulas proposed of the latter class, some of which are remarkably exact within a moderate range. The most accurate are probably those of Rankine,* already given for vapors generally:

$$\log p = A - \frac{B}{T} - \frac{C}{T^2}; \quad . \quad . \quad . \quad . \quad . \quad (1)$$

$$T = 1 \div \left[\sqrt{\left(\frac{A - \log p}{C} + \frac{B^2}{4C^2}\right)} - \frac{B}{2C}\right]; \quad . \quad . \quad (2)$$

* Steam-engine, p. 237, § 206. Ibid., pp. 559–564.

in which, for steam,

$$A = 8.2591\,; \qquad \frac{B}{2C} = 0.003441\,;$$

$$\log B = 3.43642\,;$$

$$\log C = 5.59873\,; \qquad \frac{B^2}{4C^2} = 0.00001184\,;$$

pressures being taken in pounds on the square foot and temperature in degrees Fahrenheit on the absolute scale. The experiments of Regnault and of Fairbairn and Tate have furnished the generally accepted values.

Unwin has proposed* a simpler formula than Rankine's, which, while not quite as exact, gives more manageable expressions for $\frac{dp}{dT}$ and its functions; thus, for vapors generally:

$$\log p = a - \frac{b}{T^n}\,; \quad \ldots\ldots\ldots \quad (3)$$

$$T = \left(\frac{b}{a - \log b}\right)^{\frac{1}{n}}; \quad \ldots\ldots\ldots \quad (4)$$

$$\frac{1}{p}\frac{dp}{dT} = 2.3025\frac{nb}{T^{n+1}}$$

$$= 2.3025n\frac{(a - \log p)^{\frac{n+1}{n}}}{b^{\frac{1}{n}}}; \quad \ldots\ldots \quad (5)$$

$$\frac{t}{p}\frac{dp}{dT} = 2.3025\frac{nb}{T^n}$$

$$= 2.3025n(a - \log p). \quad \ldots\ldots \quad (6)$$

---

* *Phil. Mag.*, April, 1886.

For steam, these formulas become :

$$\log p = 7.5030 - \frac{7579}{T^{1.25}}; \quad . \quad . \quad . \quad . \quad . \quad (7)$$

$$T = \left(\frac{7579}{7.5030 - \log p}\right)^{0.8}; \quad . \quad . \quad . \quad . \quad (8)$$

$$\frac{1}{p}\frac{dp}{dT} = \frac{21815}{T^{2.25}}$$

$$= \frac{(7.5030 - \log p)^{1.8}}{441.3}; \quad . \quad . \quad . \quad . \quad (9)$$

$$\frac{T}{p}\frac{dp}{dT} = \frac{21815}{T^{1.25}}$$

$$= 2.8782(7.5030 - \log p); \quad . \quad . \quad . \quad (10)$$

which expressions give remarkably exact results. Metric measures are used throughout.

137. The Specific Heats of Water and Steam vary somewhat with temperature; this variation is noted with all solids, and occurs with the vapors, although in vastly less degree; and this is one point in which they are distinguished from the gases. For all the purposes of the engineer the specific heat of either saturated steam or of steam-gas may be taken at the value obtained by Regnault, 0.305, the quantity of heat, in thermal units, demanded to raise the temperature of unity of weight of saturated steam one degree, while still keeping it saturated by the evaporation of additional water; which latter process demands the transformation of 0.695 unit of heat.

The specific heat of isolated steam-gas, or superheated steam, is given by Regnault as 0.48051, and constant.

The specific heat of water was determined by Regnault* very carefully and exactly, and the figures so obtained have been

* Mem. of the Academy of Sciences, 1847.

found capable of being very accurately represented by the following empirical formula of Rankine:*

$$C = 1 + 0.000000309(t - 39^{\circ}.1)^2, \quad . \quad . \quad . \quad . \quad (1)$$

in which t is the temperature on the common Fahrenheit scale.

The total heat demanded from t_1 to t_2 would thus be

$$h = \int_{t_1}^{t_2} C dt = t_2 - t_1 + 0.000000103[(t_2 - 39^{\circ}.1)^3 - (t_1 - 39^{\circ}.1)^3]; \quad . \quad . \quad (2)$$

and the mean specific heat for such a range of temperature is

$$\frac{h}{t_2 - t_1} = 1 + 0.000000103[(t_2 - 39^{\circ}.1)^2 + (t_2 - 39^{\circ}.1)(t_1 - 39^{\circ}.1) + (t_1 - 39^{\circ}.1)^2]. \quad . \quad . \quad (3)$$

On the Centigrade scale these expressions become

$$C = 1 + 0.000001(t - 4^{\circ})^2, \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (1a)$$

$$h = t_2 - t_1 + 0.00000033[(t_2 - 4^{\circ})^3 - (t_1 - 4^{\circ})^3], \quad . \quad . \quad . \quad (2a)$$

$$\frac{h}{t_2 - t_1} = 1 + 00000033[(t_2 - 4^{\circ})^2 + (t_2 - 4^{\circ})(t_1 - 4^{\circ}) + (t_1 - 4^{\circ})^2]. \quad . \quad . \quad . \quad . \quad (3a)$$

The specific heat of *ice* is given by M. Person as 0.504.

138. The Computation of Latent and Total Heat of Steam is readily made by means of formulas given by Regnault or based upon his work, which covered a wide range of temperature—from a little below the freezing-point to about 375° F. (190° C.). The following is the formula of Regnault for latent heat as slightly modified and corrected by Rankine for the British and metric systems, respectively:

$$l = 1091.7 - 0.695(t - 32^{\circ}) - 0.000000103(t - 39^{\circ}.1)^3; \quad . \quad (1)$$

$$l_m = 606.5 - 0.695t - 0.000000333(t - 4^{\circ})^3; \quad . \quad . \quad . \quad . \quad . \quad (1a)$$

* Trans. Royal Soc. of Edinburgh, 1851; Steam Engine, p. 246.

or, approximately, as given by the investigator,

1092 −

$$
\begin{aligned}
l &= 1092 - 0.7(t - 32^\circ) \\
&= 966 - 0.7(t - 212) \\
&= 1147 - 0.7t. \qquad \qquad (2) \\
l_m &= 606 - 0.7t. \qquad \qquad (2a)
\end{aligned}
$$

The *total heat of evaporation* is the sum of the latent and sensible heats, and may be taken as

$$
\begin{aligned}
h &= C(t_1 - t_2) + l_1 \\
&= 1091.7 + 0.305(t - 32^\circ); \qquad (3) \\
h_m &= 606.5 + 0.305t; \qquad (3a)
\end{aligned}
$$

in which the "total heat" measured is that *from* t_2 *at* t_1, the original temperature of the water and that of evaporation, and the formulas given being based on the assumption that t_1 is taken at the melting-point of ice. For any other temperature the following will give satisfactorily exact measures:

$$
\begin{aligned}
h &= 1092 + 0.3(t_1 - 32) - (t_2 - 32^\circ); \\
&= 1146 + 0.3(t_1 - 212) - (t_2 - 32^\circ); \qquad (4) \\
h_m &= 606.5 + 0.3t_1 - t_2; \qquad (4a)
\end{aligned}
$$

h being obtained in British measures and h_m in metric.

For *steam-gas*,

$$h = 1092 + 0.48(t_2 - t_1). \qquad (5)$$

Professor Unwin proposes the following for the latent heat of vaporization of steam:

$$l_m = 799 - \frac{894}{(7.5030 - \log p)^{0.8}}, \qquad (6)$$

which is found to be extremely exact. He also obtains for the expansion during change of state,

$$\Delta v_m = 10.821 \frac{l_m}{p(7.5030 - \log p)}; \qquad (7)$$

p being expressed, as above, in millimetres of mercury.

139. Factors of Evaporation measure the relative amount of heat demanded to effect the heating of water from a given temperature, t_2, and its vaporization at a higher temperature, t_1, and to simply produce vaporization at the boiling-point under atmospheric pressure, which latter is now usually taken as a standard. The value of this factor of evaporation is evidently

$$f = 1 + \frac{0.3(t_1 - 212^\circ) + (212^\circ - t_2)}{966.1}, \text{ nearly. . } \quad (1)$$

The following are values of such factors, calculated as above:

TABLE OF FACTORS OF EVAPORATION.

Boiling-point, T_1. Fahr.	Initial Temperature of Feed-water, T_2.										
	32°	50°	68°	86°	104°	122°	140°	158°	176°	194°	212°
212°	1.19	1.17	1.15	1.13	1.11	1.10	1.08	1.06	1.04	1.02	1.00
230	1.20	1.18	1.16	1.14	1.12	1.10	1.08	1.06	1.04	1.02	1.01
248	1.20	1.18	1.16	1.14	1.13	1.11	1.09	1.07	1.05	1.03	1.01
266	1.21	1.19	1.17	1.15	1.13	1.11	1.09	1.07	1.06	1.04	1.02
284	1.21	1.20	1.18	1.16	1.14	1.12	1.10	1.08	1.06	1.04	1.02
302	1.22	1.20	1.18	1.16	1.14	1.12	1.11	1.09	1.07	1.05	1.03
320	1.22	1.21	1.19	1.17	1.15	1.13	1.11	1.09	1.07	1.05	1.03
338	1.23	1.21	1.19	1.17	1.15	1.14	1.12	1.10	1.08	1.06	1.04
356	1.23	1.22	1.20	1.18	1.16	1.14	1.12	1.10	1.08	1.06	1.04
374	1.24	1.22	1.20	1.18	1.17	1.15	1.13	1.11	1.09	1.07	1.05
392	1.24	1.23	1.21	1.19	1.17	1.15	1.13	1.11	1.09	1.07	1.06
410	1.25	1.23	1.22	1.20	1.18	1.16	1.14	1.12	1.10	1.08	1.06
428	1.25	1.24	1.22	1.20	1.18	1.16	1.14	1.12	1.11	1.09	1.07

A vastly more convenient form of table is that in which the pressures at which evaporation takes place are given; thus:

FACTORS OF EVAPORATION.

Temperature of Feed-water in Degrees.		Gauge Pressure in Pounds per Square Inch Above the Atmosphere and in Atmospheres.															
		25	30	35	40	45	50	60	70	80	90	100	120	140	160	180	200
F.	C.	1.7	2.0	2.3	2.7	3.0	3.3	4.0	4.7	5.3	6.0	6.7	8.0	9.3	10.7	12	13.3
32	0	1.204	1.206	1.209	1.211	1.212	1.214	1.217	1.219	1.222	1.224	1.227	1.231	1.234	1.237	1.239	1.241
35	1.6	.201	.203	.206	.208	.209	.211	.214	.216	.219	.221	.224	.228	.231	.234	.236	.238
40	4.4	.196	.198	.201	.203	.204	.206	.209	.211	.214	.216	.219	.223	.226	.229	.231	.233
45	7.2	.190	.192	.195	.197	.198	.200	.203	.205	.208	.210	.213	.217	.220	.223	.225	.227
50	10	.185	.187	.190	.192	.193	.195	.198	.200	.203	.205	.208	.212	.215	.218	.220	.222
55	12.7	.180	.182	.185	.187	.188	.190	.193	.195	.198	.200	.203	.207	.210	.213	.215	.217
60	15.5	.175	.177	.180	.182	.183	.185	.188	.190	.193	.195	.198	.202	.205	.208	.210	.212
65	18.3	.170	.172	.175	.177	.178	.180	.183	.185	.188	.190	.193	.197	.200	.203	.205	.207
70	21.1	.165	.167	.170	.172	.173	.175	.178	.180	.183	.185	.188	.192	.195	.198	.200	.202
75	23.5	.160	.162	.165	.167	.168	.170	.173	.175	.178	.180	.183	.187	.190	.193	.195	.197
80	26.6	.154	.156	.159	.161	.162	.164	.167	.169	.172	.174	.177	.181	.184	.187	.189	.191
85	29.4	.149	.151	.154	.156	.157	.159	.162	.164	.167	.169	.172	.176	.179	.182	.184	.186
90	32.2	.144	.146	.149	.151	.152	.154	.157	.159	.162	.164	.167	.171	.174	.177	.179	.181
95	35.0	.139	.141	.144	.146	.147	.149	.152	.154	.157	.159	.162	.166	.169	.172	.174	.176
100	37.7	.134	.136	.139	.141	.142	.144	.147	.149	.152	.154	.157	.161	.164	.167	.169	.171
105	40.5	.128	.130	.133	.135	.136	.133	.141	.143	.146	.148	.151	.155	.158	.161	.163	.165
110	43.3	.123	.125	.128	.130	.131	.133	.136	.138	.141	.143	.146	.150	.153	.156	.158	.160
115	46.1	.118	.120	.123	.125	.126	.120	.131	.133	.136	.138	.141	.145	.143	.151	.153	.155
120	48.8	.113	.115	.118	.120	.121	.123	.126	.128	.131	.133	.136	.140	.143	.146	.148	.150
125	51.6	.108	.110	.113	.115	.116	.118	.121	.123	.126	.128	.131	.135	.138	.141	.143	.145
130	54.4	.102	.104	.107	.109	.110	.112	.115	.117	.120	.122	.125	.129	.132	.135	.137	.139
135	57.2	.097	.099	.102	.104	.105	.107	.110	.112	.115	.117	.120	.124	.127	.130	.132	.134
140	60.0	.092	.094	.097	.099	.100	.102	.105	.107	.110	.112	.115	.119	.122	.125	.127	.129
145	62.7	.087	.089	.092	.094	.095	.097	.100	.102	.105	.107	.110	.114	.117	.120	.122	.124
150	65.5	.082	.084	.087	.089	.090	.092	.095	.097	.100	.102	.105	.109	.112	.115	.117	.119
155	68.3	.076	.078	.081	.083	.084	.086	.089	.091	.094	.096	.099	.103	.106	.109	.111	.113
160	71.1	.071	.073	.076	.078	.079	.081	.084	.086	.089	.091	.094	.098	.101	.104	.106	.108
165	73.8	.066	.068	.071	.073	.074	.076	.079	.081	.084	.086	.089	.093	.096	.099	.101	.103
170	76.6	.061	.063	.066	.068	.069	.071	.074	.076	.079	.081	.084	.088	.091	.094	.096	.098
175	79.4	.056	.058	.061	.063	.064	.066	.069	.071	.074	.076	.079	.083	.086	.089	.091	.093
180	82.2	.050	.052	.055	.057	.058	.060	.063	.065	.068	.070	.073	.077	.080	.083	.085	.087
185	85.0	.045	.047	.050	.052	.053	.055	.058	.060	.063	.065	.068	.072	.075	.078	.080	.082
190	87.7	.040	.042	.045	.047	.048	.050	.053	.055	.058	.060	.063	.067	.070	.073	.075	.077
195	90.5	.035	.037	.040	.042	.043	.045	.048	.050	.053	.055	.058	.062	.065	.067	.070	.072
200	93.3	.030	.032	.035	.037	.038	.040	.043	.045	.048	.050	.053	.057	.060	.063	.065	.067
205	96.1	.025	.027	.030	.032	.033	.035	.038	.040	.043	.045	.048	.052	.055	.058	.060	.062
210	98.8	.020	.022	.025	.027	.028	.030	.033	.035	.038	.040	.043	.047	.050	.053	.055	.057

It is seen that the relative cost of using feed-water at any one temperature as compared with the use of water at any other temperature is as the reciprocal of their factors of evaporization. Thus if feed-water can be supplied, by means of a heater, at 210° F., where previously drawn from the mains at 50°, the relative cost of making steam will be, at 100 pounds pressure, by gauge, $\frac{1043}{1208} = 0.86$, and a gain of fourteen per cent will be effected. As will be seen later, these tables are very useful in reducing the data obtained in trials of steam-boilers to the standard.

140. **Regnault's Researches and Methods** have furnished all the essential data relating to the production of steam in the boiler and the supply of stored heat-energy to the engine.

The memoir of M. Henri Victor Regnault on "The Elastic Forces of Aqueous Vapors,"* in which he described his researches, is a most magnificent exposition of a still more remarkable series of investigations. He repeated the methods and experiments of earlier physicists, invented new ways, and finally obtained a set of data of unexampled extent and accuracy.† Regnault found that the density of aqueous vapor *in vacuo* and under feeble pressure may be calculated according to the law of Boyle and Marriotte when the fraction of saturation is less than 0.8, while the density becomes sensibly greater when approaching saturation. He further found that the density of vapor *in air*, in a state of saturation, may be similarly calculated, and the ratio of weight of equal volumes of vapor and air is a trifle less than that obtained theoretically.

The data obtained by Regnault were carefully tabulated, and curves were constructed exhibiting the variation of pressure with temperature for saturated steam for the whole range covered by his experiments. Three formulas of interpolation were used for three different parts of the scale of temperatures; for that part below the freezing-point he adopted the formula

$$F = a + b\alpha^{\tau}, \qquad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (1)$$

* *Ann. de Chimie et de Physique*, July, 1844; Mém. de l'Institut, tome xxi., p. 465 (1847); Mém. de l'Académie des Sciences, xxi. xxvi.

† *Vide* Dixon on Heat, vol. i., § 724.

in which F is the pressure, a and b constants, and α^τ a function of $\tau = t + 32°$, t being the temperature corresponding to F.

Between the freezing and boiling points Regnault used Biot's formula,

$$\log F = a + b\alpha^t - c\beta^t; \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (2)$$

and above the boiling-point,

$$\log F = a - b\alpha^\tau - c\beta^\tau; \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (3)$$

in which $\tau = t + 20$. This last answers well, also, for the whole range. In it $a = 6.2640348$; $\log b = 0.1397743$; $\log c = 0.6924351$; $\log \alpha = \bar{1}.994049292$; $\log \beta = 1.998343862$, as given by Regnault; or, according to Dixon,

$$\begin{aligned} a &= 6.263\ 509\ 686\ 5 \\ \log \alpha &= \bar{1}.998\ 343\ 377\ 8 \\ \log \beta &= \bar{1}.994\ 048\ 173\ 7 \\ \log b &= 0.692\ 450\ 419\ 2 \\ \log c &= 0.139\ 553\ 958\ 4 \end{aligned}$$

For British measures,

$$\begin{aligned} a &= 4.859\ 984\ 524\ 7 \\ \log \alpha &= \bar{1}.999\ 079\ 751\ 3 \\ \log \beta &= \bar{1}.996\ 693\ 778\ 3 \\ \log b &= 0.659\ 317\ 975\ 2 \\ \log c &= 0.020\ 517\ 432\ 4 \end{aligned}$$

A break was observed by Regnault, and is exhibited by the curves and the formulas, at the freezing-point, which had been attributed to error, the two curves cutting each other at a very small but appreciable angle; but Professor James Thomson has supposed such a break to have a real existence, and to be produced by the physical change marking the freezing-point.

141. Regnault's Tables have been reproduced in many forms, usually with additions. The Appendix, among other tables, contains the data obtained by Regnault (Table I.), and

these values are accepted as standard universally. The table here given exhibits the temperatures and corresponding pressures of saturated steam throughout the full range now used in steam-boilers and far beyond; the quantity of heat, sensible and latent, in unity of weight; the total heat of evaporation, and the density of the steam. Reference to these tables is vastly more convenient than calculation. Should it be necessary, or desirable, however, to make such calculations, the formulas already given will furnish the means. They also permit the calculation of data beyond the limits of Regnault's experiment, and are probably practically correct far beyond any pressure likely to become familiar in the operation of steam-boilers. Regnault's limit was at 230° C. (446° F.). Rankine's formula has been used beyond it.

Fairbairn and Tate's formula for volume of steam is

$$V = 25.62 + \frac{49513}{p + 0.72};$$

in which V is the volume of the steam formed at a pressure p, measured in inches of mercury, from one cubic foot of water, taken as unity and at the temperature of maximum density (see p. 272, § 135). Nystrom has used this formula in the computation of very complete tables of specific volumes of steam (see Nystrom's Pocket Book of Mechanics).

The formulas used in these calculations are elsewhere given, but are here grouped for convenience of reference. British measures are used throughout.

FORMULAS RELATING TO PROPERTIES OF STEAM.

QUANTITY.			SYMBOL.	FORMULA.
Pressure.	Above a Vacuum.	Pounds per square inch.	P	$P = \frac{p}{144}$, $\log P = 6.1007 \frac{2731.62}{t} - \frac{396944}{t^2}$
		Pounds per square foot.	p	$p = P \times 144$, $\log p = 8.2591 - \frac{2731.62}{T} - \frac{396944}{T^2}$
		Inches of mercury, at 32° Fahr.	M	$M = P \times 2.03759$
		Feet of distilled water, at temperature of maximum density.	F	$F = P \times 2.306768$
		Atmospheres.	A	$A = P \times 0.0680967$
	Above the atmosphere, in pounds per square inch.		G	$G = P - 14.685$
Temperature.	Fahrenheit's scales.		t	$t = T - 461°.2$
	Absolute scale, Fahrenheit degrees.		T	$T = 1 \div \left(\sqrt{\frac{8.2591 - \log p}{396944} + 0.00001184} - 0.003441\right)$
Quantity of heat.	Per pound of steam in British thermal units.	Required to raise the temperature of the water from 32° to t°.	S	$S = t - 32 + 0.000000103(t - 39.1)^2$
		Required to change the water into steam. (Internal latent heat.)	I	$I = L - E$
		Required to overcome the pressure of the surrounding medium. (External latent heat.)	E	$E = p \times \frac{C - v}{772}$
		Latent heat of evaporation, under constant pressure, P.	L	$L = 1091.7 - 0.695(t - 32) - 0.000000103(t - 39.1)^2$
		Total heat of evaporation above 32°.	H	$H = 1091.7 + 0.305(t - 32)$
	Total heat of evaporation per pound of steam, above 32°, in units of evaporation.		U	$U = \frac{H}{966.1}$

FORMULAS RELATING TO PROPERTIES OF STEAM—*Continued.*

QUANTITY.		SYMBOL.	FORMULA.
Foot-pounds of energy, in latent heat of evaporation, per cubic foot of steam.		l	$l = 2.3026 \times p \times \left(\frac{2731.62}{T} + \frac{793888}{T^2}\right)$
Weight.	Of a cubic foot of steam, in pounds.	W	$W = \frac{l}{772 \times L}$
	Of a cubic foot of distilled water, in pounds, at temperature t.	w	$w = \frac{62.425}{v}$
Volume.	Of a pound of steam, in cubic feet.	C	$C = \frac{1}{W}$
	Ratio of volume of steam to volume of equal weight of distilled water at temperature of maximum density.	V	$V = C \times 62.425$
	Ratio of volume of distilled water, at temperature T, to volume of equal weight at temperature of maximum density.	v	For temperatures from 32° to 70°, $v = 1.00012 - 0.000033914(t - 32) + 0.0000023822(t - 32)^2 - 0.000000006403(t - 32)^3$ For temperatures above 70°, $v = 0.99781 + 0.00006117(t - 32) + 0.000001059(t - 32)^2$

142. The Stored Energy in Steam at any pressure and temperature is now easily ascertained by calculation, in accordance with the first law of thermodynamics.

The first attempt to calculate the amount of energy latent in the water contained in steam-boilers, and capable of greater or less utilization in expansion by explosion, was made by Mr. George Biddle Airy,* the Astronomer Royal of Great Britain, in the year 1863, and by the late Professor Rankine† at about the same time.

Approximate empirical expressions are given by the latter for the calculation of the energy and of the ultimate volumes assumed by unit weight of water during expansion, as follows, in British and in metric measures:

$$U = \frac{772(T - 212)^2}{T + 1134.4}; \qquad U_m = \frac{423.55(T - 100)^2}{T + 648};$$

$$V = \frac{36.76(T - 212)}{T + 1134.4}; \qquad V_m = \frac{2.29(T - 100)}{T + 648}.$$

These formulas give the energy in foot-pounds and kilogrammetres, and the volumes in cubic feet and cubic metres. They may be used for temperatures not found in the tables to be given, but, in view of the completeness of the latter, it will probably be seldom necessary for the engineer to resort to them.

The quantity of work and of energy which may be liberated by the explosion, or utilized by the expansion, of a mass of mingled steam and water has been shown by Rankine and by Clausius, who determined this quantity almost simultaneously, to be easily expressed in terms of the two temperatures between which the expansion takes place.

When a mass of steam, originally dry, but saturated, so expands from an initial absolute temperature, T_1, to a final absolute temperature, T_2, if J is the mechanical equivalent of the unit of heat, and H is the measure, in the same units, of

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* "Numerical Expression of the Destructive Energy in the Explosions of Steam Boilers."

† "On the Expansive Energy of Heated Water."

the latent heat per unit of weight of steam, the total quantity of energy exerted against the piston of a non-condensing engine, by unity of weight of the expanding mass, is, as a maximum,

$$U = JT_2\left(\frac{T_1}{T_2} - 1 - \text{hyp log}\,\frac{T_1}{T_2}\right) + \frac{T_1 - T_2}{T_1}H. \quad . \quad . \quad \text{(A)}$$

This equation was published by Rankine a generation ago.*

When a mingled mass of steam and water similarly expands, if M represents the weight of the total mass and m is the weight of steam alone, the work done by such expansion will be measured by the expression,

$$U = MJT_2\left(\frac{T_1}{T_2} - 1 - \text{hyp log}\,\frac{T_1}{T_2}\right) + m\frac{T_1 - T_2}{T_2}H. \quad \text{(B)}$$

This equation was published by Clausius in substantially this form.†

It is evident that the latent heat of the quantity m, which is represented by mH, becomes zero when the mass consists solely of water, and that the first term of the second member of the equation measures the amount of energy of heated water which may be set free, or converted into mechanical energy by explosion. The available energy of heated water, when explosion occurs, is thus easily measurable.

The computers of the tables given in the Appendix were Messrs. Ernest H. Foster, and Kenneth Torrance. The tables range from 20 pounds per square inch (1.4 kgs. per sq. cm.) up to 100,000 pounds per square inch (7030.83 kgs. per sq. cm.), the maximum probably falling far beyond the range of possible application, its temperature exceeding that at which the metals retain their tenacity, and in some cases exceeding their melting-points. These high figures are not to be taken

* Steam-engine and Prime Movers, p. 387.

† Mechanical Theory of Heat, Browne's translation, p. 283.

as exact. The relation of temperature to pressure is obtained by the use of Rankine's equation, of which it can only be said that it is wonderfully exact throughout the range of pressures within which experiment has extended, and within which it can be verified. The values estimated and tabulated are probably quite exact enough for the present purposes of even the military engineer and ordnance officer. The form of the equation, and of the curve representing the law of variation of pressure with temperature, indicates that, if exact at the familiar pressures and temperatures, it is not likely to be inexact at higher pressures. The curve at its upper extremity becomes nearly rectilinear.

The table presents the values of the pressures in pounds per square inch above a vacuum, the corresponding reading of the steam-gauge (allowing a barometric pressure of 14.7 pounds per square inch), the same pressures reckoned in atmospheres, the corresponding temperatures as given by the Centigrade and the Fahrenheit thermometers, and as reckoned both from the usual and the absolute zeros. The amount of the available stored energy of a unit weight of water, of the latent heat in a unit weight of steam, and the total available heat-energy of the steam, are given for each of the stated temperatures and pressures throughout the whole range in British measures, atmospheric pressures being assumed to limit expansion. The values of the latent heats are taken from Regnault, for moderate pressures, and are calculated for the higher pressures, beyond the range of experiment, by the use of Rankine's modification of Regnault's formula.

Studying the table, the most remarkable fact noted at the lower pressures is the enormous difference in the amounts of energy, in available form, contained in the water and in the steam, and between the energy of sensible heat and that of latent heat, the sum of which constitutes the total energy of the steam. At 20 pounds per square inch above zero (1.36 atmos.), the water contains but 145.9 foot-pounds per pound; while the latent heat is equivalent to 16,872.9 foot-pounds, or more than 115 times as much; i.e., the steam contains 116 times as much energy in the form of latent heat per pound, as

does the water, from which it is formed, at the same temperature. The temperature is low; but the amount of energy expended in the production of the molecular change resulting in the conversion of the water into steam is very great, in consequence of the enormous expansion then taking place. At 50 pounds the ratio is 20 to 1; at 100 pounds per square inch it is 14 to 1, at 500 it is 5 to 1; while at 5000 pounds the energy of latent heat is but 1.4 that of the sensible heat. The two quantities become equal at about 7500 pounds. At the highest temperature and pressure tabled, the same law would make the latent heat negative; it is of course uncertain what is the fact at that point.

At 50 pounds per square inch the energy of heated water is 2550.4 foot-pounds, while that of the steam is 68,184, or enough to raise its own weight to a height, respectively, of a half-mile and of 12 miles. At 75 pounds the figures are 4816 and 90,739, or equivalent to the work demanded to raise the unit weight to a height of four fifths, and of about 17 miles respectively. At 100 pounds the heights are over one mile for the water and above 20 miles for the steam.

Comparing the energy of water and of steam in the steam-boiler with that of gunpowder, as used in ordnance, it will be found that at high pressures the former become possible rivals of the latter. The energy of gunpowder is somewhat variable with composition and perfection of manufacture, and is very variable in actual use, in consequence of the losses in ordnance due to leakage, failure of combustion, or retarded combustion in the gun. Taking its value at what the Author would consider a fair figure, 250,000 foot-pounds per pound, it is seen that, as found by Airy, a cubic foot of heated water, under a pressure of 60 or 70 pounds per square inch, has about the same energy as one pound of gunpowder. The gunpowder exploded has energy sufficient to raise its own weight to a height of nearly 50 miles, while the water has enough to raise its weight about one sixtieth that height. At a low red heat water has about 40 times this latter amount of energy in a form to be so expended. One pound of steam, at 60 pounds pressure, has about one third the energy of a pound of gunpowder.

At 100 pounds it has as much energy as two fifths of a pound of powder, and at higher pressures its energy increases very slowly.

143. The Curves of Stored Energy are most instructive. Plotting the tabulated figures and determining the form of the

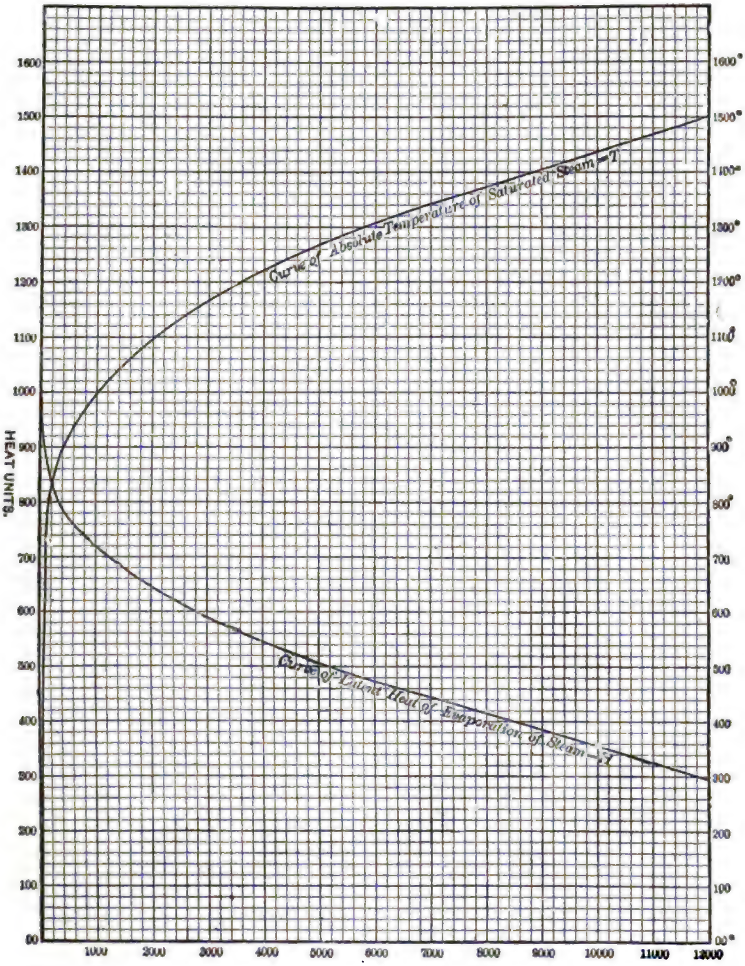

FIG. 71.—CURVE OF HEAT IN STEAM.

curve representing the law of variation of each set, we obtain the peculiar set of diagrams exhibited in the accompanying engraving. In Fig. 71 are seen the curves of absolute tempera-

ture and of latent heat as varying with variation of pressure. They are smooth and beautifully formed lines, having no relation to any of the familiar curves of the text-books on co-ordi-

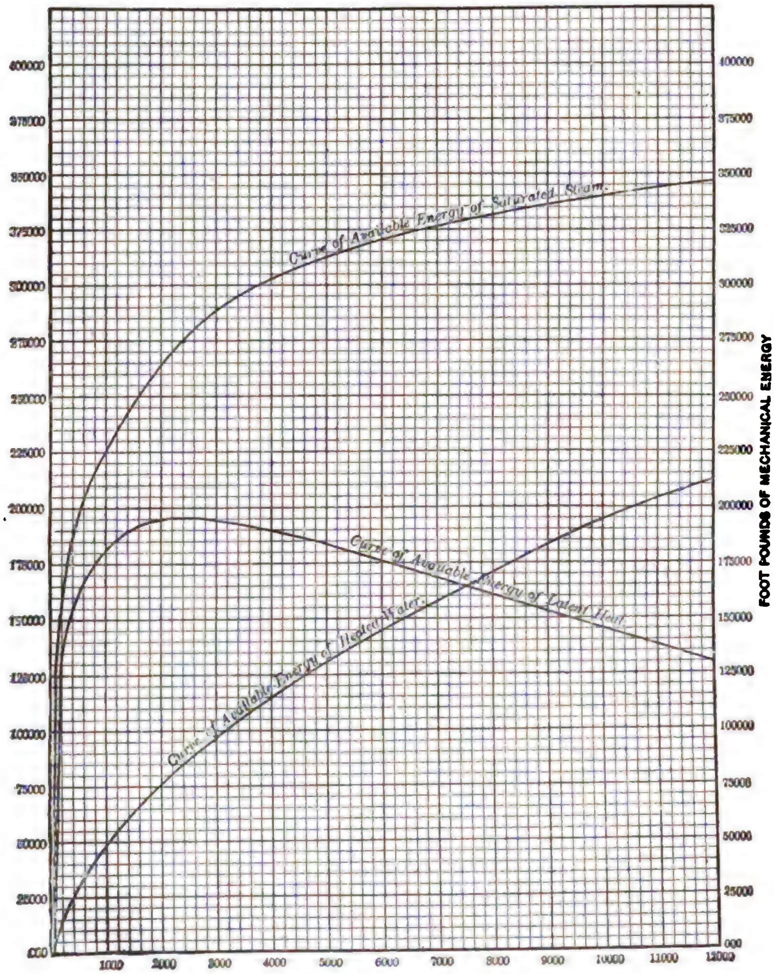

FIG. 72.—CURVE OF HEAT-ENERGY IN STEAM.

nate geometry. In Fig. 72 are given the curves of available energy of the water of latent heat and of steam. The first and third have evident kinship with the two curves given in

the preceding illustration; but the curve of energy of latent heat is of an entirely different kind, and is not only peculiar in its variation in radius of curvature, but also in the fact of presenting a maximum ordinate at an early point in its course. This maximum is found at a pressure of about one ton per square inch—a pressure easily attainable by the engineer.

Examining the equations of those curves, it is seen that they have no relation to the conic sections, and that the curve, the peculiarities of which are here noted, is symmetrical about one of its abscissas, and that it must have, if the expression holds for such pressures, another point of contrary flexure at some enormously high pressure and temperature. The formula is not, however, a "rational" one, and it is by no means certain that the curve is of the character indicated; although it is exceedingly probable that it may be. The presence of this characteristic point, should experiment finally confirm the deduction here made, will be likely to prove interesting, and it may be important; its discovery may possibly prove to be useful.

The curve of energy of steam is simply the curve obtained by the superposition of one of the two preceding curves upon the other. It rises rapidly at first, with increase of temperature, then gradually rises more slowly, turning gracefully to the right, and finally becoming nearly rectilinear. The curve of available energy, of heated water, exhibits similar characteristics; but its curvature is more gradual and more uniform.

144. The Actual Power of Steam and of Boilers evidently depends upon the efficiency of the method of application, and on the apparatus employed. The quantity of heat-energy supplied to the engine and yielded by the generator has been seen to be easily calculable by simply multiplying the quantity of heat given to the steam by the fuel, by the mechanical equivalent of heat. The amount available as energy may be the total quantity so supplied, as when the steam is condensed in heating buildings or otherwise, and is returned as feed-water to the boilers; or it may be any less amount, accordingly as the method of utilization is more or less effective. The tables given in the Appendix furnish the data for calcu-

lation in any case in which the efficiency of transfer and of transformation is known. Where no constant value can be assumed for the efficiency of the system employed, it is sometimes, nevertheless, found to be important to establish a standard conventionally. Thus, in the calculation of available stored energy, as given in the Appendix, Table II., it was assumed that the steam would be expanded to atmospheric pressure. Similarly, convention has established the unit horse-power of steam-boilers, in order to afford a standard of comparison in test-trials, and to give a means of rating boilers by the designer, the builder, or the purchaser and user.

The operation of boilers occurs under a wide range of actual conditions—the steam-pressure, the temperature of feed-water, the rate of combustion and of evaporation, and, in fact, every other variable condition, differing in any two trials to such an extent that direct comparison of the totals obtained, as a matter of information regarding the relative value of the boilers, or of the fuel used, becomes out of the question. It has hence gradually come to be the custom to reduce all results to the common standard of weight of water evaporated by the unit-weight of fuel, the evaporation being considered to have taken place at mean atmospheric pressure, and at the temperature due that pressure, the feed-water being also assumed to have been supplied at the same temperature. This, in technical language, is said to be the "equivalent evaporation from and at the boiling-point" (212° Fahr., 100° C.). This standard has now become generally incorporated into the science and the practice of steam-engineering. The "Unit of Evaporation" is one pound of water at the boiling-point, evaporated into steam of the same temperature. This is equivalent to the utilization of 965.7 British thermal units per pound of water so evaporated. The economy of the boiler may thus be expressed by the number of units of evaporation obtained per pound of combustible.

145. The Horse-power of Steam-Boilers must always be reckoned on an assumed basis involving the amount of heat supplied from the furnace, the conditions determining the availability of that heat as stored, and the circumstances con-

trolling its expenditure and transformation. The term must evidently be purely conventional and technical, and its definition must be strictly limited.

The character and magnitude of the unit to be chosen to express the "power" of the steam-boiler is not fully settled, though the subject has attracted much attention among engineers. It is evident that since the boiler is merely an apparatus for the generation of steam, and since the province of the steam-engine is to develop power from that steam, and with a degree of efficiency which may vary enormously, it is certain that we have no natural unit of power for steam-boilers. It may even be asserted that no natural unit can exist. The most scientific system of power-rating yet proposed considers the power of a boiler to be that expended by it in driving out all the steam which it makes against the pressure of the atmosphere, a system suggested by Nystrom.*

The weight of water to be evaporated per hour at any given pressure to produce one horse-power as the equivalent of its natural effect without expansion, by impelling a piston against its load, is calculable with sufficient accuracy by the formula of Nystrom:

$$\text{H. P.} = \frac{Vp(v-1)}{13748.4}; \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (1)$$

in which V is the volume of steam in cubic feet, p the absolute pressure in pounds per square inch, and v the volume of steam relatively to that of water at the freezing-point. By this method we obtain the following values:

* Mechanics, 18th Ed., p. 562.

p	H. P. per Cu. Ft.	Lbs. per H. P.
5	1.6600	29.852
10	1.7253	28.723
14.7	1.7540	28.252
25	1.7879	27.717
40	1.8238	27.170
60	1.8649	26.573
80	1.9033	26.038
100	1.9406	25.537
125	1.9865	24.945
150	2.0321	24.387

What is sometimes called the "boiler-heat horse-power"* is the power corresponding to the energy imparted to the steam by its evaporation within the boiler. This power is measured by dividing the weight of steam made by that required to produce unity of power, and the latter quantity is obtained by dividing the energy in foot-pounds of one horse-power per hour by the mechanical equivalent of the latent heat of steam; i.e.,

$$w = \frac{1,980,000}{966 \times 772} = 2.65 \text{ lbs.}$$

Taking as a standard the quantity of steam demanded by a *perfect* engine, having no clearance, receiving steam at boiler-pressure, and expanding it down to a perfect vacuum, or to the atmospheric pressure, we may readily obtain figures for the weights demanded by which to rate steam-boilers, should it be found necessary to resort to such an ideal system. For such cases, Zeuner's† figures are as below:

* "Boiler-power and Boiler-heating Surface," by Professor R. H. Smith, *Industries*, July 1, 1887.

† Warme Theorie.

Pressure Atmospheres.	Water per Horse-power per Hour.			
	Non-condensing Engine.		Condensing Engine.	
	Lbs.	Kilogs.	Lbs.	Kilogs.
3	33	15½	13	6
4	26	12	12	5½
5	23	10½	11½	5¼
6	21	9½	11	5
8	18	8	10½	4¾
10	16½	7½	10	4½

In this case the rated power of the boiler would be obtained by dividing the weight of steam made per hour by the proper figure from the above table.

Assuming the actual kinetic energy of the issuing steam to measure the actual available power of the boiler, we find that if the size of the orifice is just sufficient to discharge the steam as rapidly as it is generated, the work done by the boiler will be

$$U = \frac{wv^2}{2g}, \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (1)$$

and the power

$$\text{H. P.} = \frac{wv^2}{2g} \div 550, \quad \text{or} \quad \text{H. P.} = \frac{w_m v^2_m}{150 g_m}, \quad (2)$$

when w is the weight of steam made, and v its velocity of outflow per second, the one expression being in British, the other in metric measures.

Again taking Zeuner's figures, we have

Pressure Atmospheres.	Velocities per Second. Metres.	Feet.
3	185	607
4	208	681
5	227	734
6	230	775
8	255	835
10	260	879

and the horse-power actually delivered on this basis would be obtained by inverting these values in the expression above. So using them, we obtain for the power of the boiler,

Pressure Atmospheres.	H. P. $= \frac{wv^2}{2g} \div 550 =$	$\frac{w_m v^2_m}{2gm} \div 75.$
3	$112w$ in lbs.	$51w_m$ in kilos.
4	$140w$	$64w_m$
5	$165w$	$75w_m$
6	$184w$	$84w_m$
8	$201w$	$91w_m$
10	$237w$	$108w_m$

The work done by the boiler is thus obtained by multiplying the weight of steam made per second by the figures here given.

This system may be called the *natural* system of rating power. Where a similar system is adopted, but the total resistance of the atmosphere is allowed for, as proposed by Nystrom for the "legal" horse-power, the quantity of heat and of steam demanded is increased, at usual pressures, about one half. Nystrom proposed to assume a fixed rate of combustion and proportions of parts. His method may be illustrated as follows:

A cubic foot of water, when evaporated, forms a definite volume of steam; and if we take the product of the volume of water evaporated per hour, the increase of volume by its conversion into steam, the pressure of the steam, and divide this product by 1,980,000, the quotient, which is the power this steam can develop in a non-condensing engine, without expansion, is the horse-power of the boiler. Suppose, for example, that a boiler evaporates 25 cubic feet of water per hour, and that the pressure of the steam above the atmosphere is 130 lbs. per square inch, or 18,720 lbs. per square foot. The relative volume of steam of this pressure is 192.83, so that the increase of volume for each cubic foot of water, on its conversion into steam, is 191.83 cubic feet, and the horse-power of the boiler is the product of 25,191.83, and 18,720 divided by 1,980,000, or 45.3 +.

He would take the power of a boiler to be

$$\text{H. P.} = \sqrt{\frac{FS\sqrt{p}}{10}}; \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \qquad (2)$$

in which formula F and S are the areas of grate and heating surface in square feet. Thus a boiler having 100 square feet of grate and 3000 feet of heating surface, at 75 pounds pressure above vacuum, would rate at

$$\text{H. P.} = \sqrt{\frac{100 \times 3000 \times \sqrt{75}}{10}} = 510;$$

which is far above the usual power of steam-boilers with natural draught.

Small engines, according to Buel, demand steam, ordinarily, as below:

FEED-WATER REQUIRED BY SMALL ENGINES.

Pressure of Steam in Boiler, by Gauge.	Pounds of Water per effective Horse-power per Hour.	Pressure of Steam in Boiler, by Gauge.	Pounds of Water per effective Horse-power per Hour.
10	118	60	75
15	111	70	71
20	105	80	68
25	100	90	65
30	93	100	63
40	84	120	61
50	79	150	58

Pressures lower than 60 pounds are not usually adopted for small engines. Good examples of such engines have been found by the Author to demand from 25 to 33 per cent less steam, or feed-water, than is above given.

The following are considered by the Author as fair estimates of water and steam consumption for the best classes of engines in common use, when of moderate size and in good order:

WEIGHTS OF FEED-WATER AND OF STEAM.

NON-CONDENSING ENGINES.

Steam Pressure.		Pounds per H. P. per Hour.—Ratio of Expansion.					
Atmospheres.	Lbs. per sq. in.	2	3	4	5	7	10
3	45	40	39	40	40	42	45
4	60	35	34	36	36	38	40
5	75	30	28	27	26	30	32
6	90	28	27	26	25	27	29
7	105	26	25	24	23	25	27
8	120	25	24	23	22	22	21
10	150	24	23	22	21	20	20

CONDENSING ENGINES.

2	30	30	28	28	30	35	40
3	45	28	27	27	26	28	32
4	60	27	26	25	24	25	27
5	75	26	25	25	23	22	24
6	90	26	24	24	22	21	20
8	120	25	23	23	22	21	20
10	150	25	23	22	21	20	19

It is considered usually advisable to assume a set of practically attainable conditions in average good practice, and to take the power so obtainable as the measure of the power of the boiler in commercial and engineering transactions. The unit generally assumed has been usually the weight of steam demanded per horse-power per hour by a fairly good steam-engine. This magnitude has been gradually decreasing from the earliest period of the history of the steam-engine. In the time of Watt, one cubic foot of water per hour was thought fair; at the middle of the present century, ten pounds of coal was a usual figure, and five pounds, commonly equivalent to about forty pounds of feed-water evaporated, was allowed the best engines. After the introduction of the modern forms of engine this last figure was reduced twenty-five per cent, and the most recent improvements have still further lessened the consumption of fuel and of steam. By general consent, the unit has now become thirty pounds of dry steam per horse-power per hour, which represents the performance of good non-condensing mill-engines. Large engines, with condensers and

compounded cylinders, will do still better. A committee of the American Society of Mechanical Engineers* recommended thirty pounds as the unit of boiler-power, and this is now generally accepted. They advised that the commercial horse-power be taken as *an evaporation of* 30 *pounds of water per hour from a feed-water temperature of* 100° *Fahr. into steam at* 70 *pounds gauge pressure*, which may be considered to be equal to 34½ units of evaporation, that is, to 34½ pounds of water evaporated from a feed-water temperature of 212° Fahr. into steam at the same temperature. This standard is equal to 33,305 British thermal units per hour.†

It was the opinion of this committee that a boiler rated at any stated power should be capable of developing that power with easy firing, moderate draught, and ordinary fuel, while exhibiting good economy, and at least one third more than its rated power to meet emergencies.

Any increase of temperature derived from a heater should not be credited to the efficiency of the boiler except by agreement; and in the latter case tests should be made only with feed-water of the temperature observed during the regular operation of the boiler.

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* Trans., vol. vi., Nov. 1881.

† According to the tables in Porter's Treatise on the Richards Steam-engine Indicator, which tables the committee adopt, an evaporation of 30 pounds of water from 100° F., into steam at 70 pounds pressure, is equal to an evaporation of 34.488 pounds from and at 212°; and an evaporation of 34½ pounds from and at 212° F. is equal to 30.010 pounds from 100° F., into steam at 70 pounds pressure.

The "unit of evaporation" being equal to 965.7 thermal units, the commercial horse-power = 34.488 × 965.7 = 33.305 thermal units.

CHAPTER VII.

THE DESIGN OF THE STEAM-BOILER.

146. **The Design of the Steam-Boiler** is a problem in construction which involves vastly more than the mere application of chemical and physical principles, and the calculation of areas of grate and heating surfaces. The first step in its solution is the study of the conditions under which the steam is to be produced and utilized; the location and space available; the kind and cost of fuel; the nature and availability of the supply of feed-water; the pressure to be adopted; the facilities to be obtained for repairs; and many other conditions, of which the financial and commercial are as important as any others, must all be taken into careful consideration.

The problem, stated in the most general and comprehensive way, may be said to be the following:

Required: To determine what type, proportions, size, and construction of boiler may be made, in the location chosen, and under all the natural and artificial conditions found there to exist, to supply a given amount of steam at least total risk and cost.

The business aspects of the case must be as conscientiously studied by the designing engineer as those of pure engineering.

The design of the steam-boiler is thus a problem in engineering which demands careful consideration, accurate knowledge of the principles controlling proportions and performance, and perfect familiarity with the conditions to be met in the case in hand.

147. **The Choice of Type of Boiler and its Location** is the first step to be taken preparatory to commencing the design. The type best adapted for the special case is determined by the conditions of location and purpose, as whether station-

ary, portable, locomotive, or marine; by the pressure and quantity of steam demanded; by the character of the feed-water and fuel, and the cost of obtaining it; by the facilities to be had for repairs, etc.

Where the boiler is to be used on land, the standard locomotive and stationary boilers may be used, if found otherwise advisable; but on shipboard it is essential that the boiler should be "self-contained," and the common stationary boilers cannot be employed. Each application is best made, as a rule, by the employment of some one of those forms which have been classed above, and certain types are thus standard for each location.

Among stationary boilers the plain cylindrical is chosen when the cost of fuel is low, when the feed-water is bad, or when the facilities for repairing are not good. As the necessity for economy in fuel-consumption becomes greater, and when the character of the feed-water is good, the more complicated flue or tubular boilers are selected; or the dictates of prudence may lead to the selection of some one of the so-called "safety" or "sectional" boilers, even where cost and other considerations would weigh against them.

The most common form of stationary boiler in the United States, in ordinary good locations, is the cylindrical tubular boiler; in Great Britain the Cornish and the Galloway boilers are much used; while on the continent of Europe the "elephant" boiler is more common. In all directions, however, the safer forms of boiler are gaining ground.

The "portable" boiler is usually an upright tubular, with firebox beneath, for very small powers, and a horizontal boiler of the locomotive type for larger sizes. It must always be "self-contained" in the sense of having no "setting," and is commonly made the foundation or bed for its attached engine, somewhat as in locomotives.

The locomotive boiler has become fixed in type, and nearly fixed in proportions. All builders adopt the horizontal, cylindrical tubular shell with firebox. Here, as in all cases in which high pressures are employed, cylindrical or strongly stayed surfaces are found essential to safety and durability. Many other

designs of boiler have been proposed and experimentally employed for locomotives, but none has survived.

The marine steam-boiler is the product of a long process of evolution which has led to the gradual reduction of a variety of forms to a few standards. Thus, at sea, the "drum" or Scotch boiler, described in article 19, has become almost universally adopted where high pressures are employed, as it is stronger, more compact, and more economical than its rivals, and is self-contained.

The location of a boiler is sometimes a matter of choice with the engineer preparing the plans, and may be one of serious importance. Where possible it should always be so chosen that the boiler may be easy of access for inspection and repair; it should be free from special danger to lives or surrounding property in case of accident, and the site selected should be dry and well protected against the weather. The nearer the engine or other point at which its steam is delivered the better. Only sectional boilers should be placed under buildings. Shell-boilers should have boiler-houses constructed for them apart from the larger and more important structures to which they are auxiliary, and this precaution is especially advisable for cases, as mills, in which many lives may be endangered. The risk involved is not great where these boilers are well designed and constructed; but the prudent engineer avoids even moderate risk where a life is involved.

When the space is restricted in floor-area, but of good height, the upright tubular boiler is selected; if the floor-area is unrestricted, but head-room is small, the horizontal forms of boiler are chosen. Good forms of "safety" boilers may be placed wherever they can be given room, provided they are accessible for inspection, cleaning, and repairs.

148. **The Choice of Fuel and of Method of Combustion** is commonly necessarily made before the design can be proceeded with. The fuel is, as a rule, selected mainly with a view to commercial efficiency; but the presence of any observable quantity of sulphur in coal justifies its rejection at even considerable pecuniary sacrifice. That fuel is best which produces the required quantity of steam with certainty and regularity

under the given conditions, and at minimum total cost for purchase, transportation and handling, storage, interest and insurance, and wear and tear of apparatus. As a rule, the least costly fuels are most economical, if the furnace is properly adapted to them; but it is not always so, and the user will generally solve the problem by experiment and experience. The conditions of the market are very apt to control, and anthracite fuel in the Eastern United States, bituminous coals throughout the West, and wood in forested countries are naturally the staple fuels. On the border lines, or even within either territory, prices may be so adjusted that the question may be difficult to decide until after prolonged trial of two or more kinds which may be available. In the case of the "soft" coals the decision of the question whether the fuel shall be used in its natural state, or coked, may often demand consideration. For metallurgical purposes coke is commonly used, but for steam-boilers the raw coal is most generally adopted.

The combustion may be produced by either a natural chimney draught or a forced draught, created by a fan, a steam-jet, or other artificial means. With very fine coal, or where the grate-area or the boiler itself is so small as to make the rate of combustion due to natural draught insufficient, the blast is employed. The locomotive and the torpedo-boat illustrate this case. A closed fire-room, made air-tight, and into which the blast is driven and allowed to enter the furnace precisely as with a chimney draught, is regarded by many engineers as the best method of securing rapid combustion. Where the area of heating-surface is the same in proportion to the amount of coal burned, this system is fully as economical as the others. The proportion of heating to grate surface being fixed, or nearly constant, as is common, the slower combustion, down to certain limits is naturally the more efficient. Natural draught is to be preferred where the desired amount of steam may be made by that system.

149. **The Conditions of Efficiency** in steam-boilers are those affecting the production, the transfer, and the storage of the heat-energy derivable from the fuel. These have already

been considered. *En resumé:* the efficient production of heat requires the concentrated combustion of the fuel, with the minimum air-supply consistent with the complete combination of its oxidizable elements with oxygen, and the attainment of maximum temperature. The efficient transfer and storage in the steam of this heat demands that it be liberated at maximum temperature, that the heating-surfaces be of great extent in proportion to the weight of fuel burned and to the quantity of heat liberated, and that these surfaces be effective in absorption of heat. The formula deduced in Chapter IV. for efficiency of heating-surface gives a measure of the efficiency of the boiler when the value of the fuel is known, and includes efficiency of transfer and of storage.

150. **The Principles of Design**, in the case of the steam-boiler, involve those of strength of materials and of structures, the determination of the size, form, and proportions of parts; the relation of area of heating and of grate surface to fuel burned; the character and proportions of accessory parts; in fact, the application of all the data and the laws which have been studied in the preceding portions of this work. The designing engineer must determine the form and proportions of a vessel in which is to be generated a given quantity of steam with satisfactory efficiency and safety, and with as nearly permanent commercial success as possible.

The settlement of the general proportions of the structure is made with reference to the above considerations; but general experience has brought these proportions into a fairly definite relation, and, as an illustration, the better classes of boiler rarely have a less ratio of heating to grate surface, where natural draught is adopted, than about 25 to 1, or a higher ratio than 40 to 1. With more intense combustion and forced draught this proportion is considerably increased. The best proportion is probably usually capable of fairly exact calculation by a method to be considered at some length in a later chapter. Boiler-power is very often calculated, in cases of ordinary practice, by allowing a certain number of square feet of heating-surface to the horse-power. Thus, the following may be taken as a fair average set of figures:

Careful calculation should be resorted to in every important case.

In designing boilers the effort of the engineer should be—

(1) To secure complete combustion of the fuel without permitting dilution of the products of combustion by excess of air. A combustion-chamber is usually desirable.

(2) To secure as high temperature of furnace as possible.

(3) To so arrange heating-surfaces that, without checking draught, the available heat shall be most completely taken up and utilized and the most complete and rapid circulation secured, both for the water and for the furnace-gases.

(4) To make the form of boiler so simple that it may be constructed without mechanical difficulty or excessive expense, and to arrange for ample water-surface, as well as large steam and water capacity, so as to insure against serious fluctuation of steam-supply.

(5) To give it such form that it shall be durable, under the action of hot gases, and of corroding elements of the atmosphere.

(6) To make every part accessible for cleaning and repairs.

(7) To make all parts as nearly as possible uniform in strength, and in liability to loss of strength with age, so that the boiler, when old, shall not be rendered useless or dangerous by local defects.

(8) To adopt a reasonably high "factor of safety" in proportioning parts, and to provide against irregular strains of all kinds.

(9) To provide efficient safety-valves, steam-gauges, mud-drums, and other appurtenances.

(10) To secure intelligent and very careful management.

In securing complete combustion—the first of these desiderata—an ample supply of air and its thorough intermixture with the

combustible elements of the fuel is essential; for the second—high temperature of furnace—it is necessary that the air-supply shall not be in excess of that absolutely needed to give complete combustion. The efficiency of a furnace is measured by

$$E = \frac{T - T^1}{T - t},$$

in which E represents the ratio of heat utilized to the whole calorific value of the fuel; T is the furnace temperature; T^1 the temperature of the chimney, and t that of the external air. Hence the higher the furnace-temperature and the lower that of chimney, the greater the proportion of available heat.

It is further evident that, however perfect the combustion, no heat can be utilized if either the temperature of chimney approximates to that of the furnace, or if the temperature of the furnace is reduced by dilution to that of the chimney. Concentration of heat in the furnace is secured, in some cases, by special expedients, as by heating the entering air, or, as in the Siemens gas-furnace, heating both the combustible gases and the supporter of combustion. Detached fire-brick furnaces have an advantage over the "fireboxes" of steam-boilers in their higher temperature; surrounding the fire with non-conducting and highly heated surfaces is an effective method of securing high furnace-temperature.

In arranging heating-surface, the effort should be to impede the draught as little as possible, and so to place them that the circulation of water within the boiler should be free and rapid at every part reached by the hot gases.

The direction of circulation of water on the one side and of gas on the other side the sheet should, whenever possible, be opposite. The cold water should enter where the cooled gases leave, and the steam should be taken off farthest from that point. The temperature of chimney-gases has thus been reduced by actual experiment to less than 300° Fahr., and an efficiency equal to 0.75 to 0.80 the theoretical is attainable.

The extent of heating-surface simply, in all of the best forms of boiler, determines the efficiency, and the disposition

of that surface seldom affects it to any great extent. The area of heating-surface may also be varied within very wide limits without greatly modifying efficiency. A ratio of 25 to 1 in flue and 30 to 1 in tubular boilers represents the relative area of heating and grate surfaces in the practice of many of the best-known builders.

The factor of safety is usually too low. The boiler should be built strong enough to bear a pressure at least six times the proposed working-pressure. As it grows weak with age, it should be occasionally tested to a pressure at least double the working-pressure, which latter should be reduced gradually to keep within the bounds of safety.

151. **The Controlling Ideas** *in designing* dictate the following procedure. The engineer determines—

(1) The height of chimney, and rate of combustion desirable or practicable.

(2) The type of boiler, having regard to the character of water to be used as "feed," and the costs of construction, operation, and maintenance.

(3) The quantity of steam that will be demanded.

(4) The efficiency of boiler that it will be economical to secure, according to the principles to be given, and thus the ratio of heating to grate surfaces.

(5) The kind and the quantity of fuel required, with the given or proposed efficiency, to produce the demanded quantity of steam.

(6) The total areas of grate and of heating surface required to burn that fuel and to make that steam.

(7) The forms, sizes, and proportions of details.

The dimensions and proportions of the boiler plant being thus determined, the engineer decides what amount of power shall be obtained from a single boiler, and thus how many boilers are to be constructed, the area of heating and grate surface to be given each; and he finally decides upon the form of setting, and method of making steam and water connections.

It then remains only to make a drawing of the boiler, which shall show its form and dimensions, the arrangement of

stays, pipes, safety, and other attachments, and the setting. The first plan constructed will usually require some modification to adapt it exactly and satisfactorily to the wants of the user; which changes being made, the boiler may be constructed from the drawing. The thickness of shell, size of tubes or flues, sizes, methods, and distribution of stays, and similar matters of detail, are settled by well-known rules of practice, or by the consideration of the peculiar conditions met with in the case in hand.

Especial care should be taken to give all parts ample strength, with a fair and safe allowance for corrosion; to see that every part is easily accessible for inspection and repair; that all details are of good form and proportions; and that all accessories and attachments are the best and safest of their kind.

The Steam-pressure to be adopted will necessarily be one of the first matters to be considered and settled; both because it has an important bearing upon the efficiency of the engine and because it must be kept in view in the selection of the type and size of boiler. The tendency is constantly in the direction of higher steam-pressure, and the consequent adoption of the simpler, stronger, and safer kinds of boiler. This directly conflicts with the commercial considerations affecting boiler-construction, especially of the common forms of shell-boiler. The larger the boiler, as a rule, the cheaper, comparatively, its construction, the less the cost of setting and of installation, and the higher its economy in operation. A large shell, however, must be made of thicker iron, and is always somewhat less absolutely safe than a similar smaller structure.

A limit is thus being continually approached because of the fact that the net gain is less and less as the increase occurs at higher pressures. An increase from 100 to 200 pounds may give a calculated gain of 12 or 15 per cent; but the net gain will be actually much less, and may not be enough to compensate the increased costs and risks. At the present day, pressures of 125 to 150 pounds are not unusual; but many engineers consider it inadvisable to go much farther in the direction of increasing pressure, and the tendency of modern practice is

to restrict the adoption of such higher pressures to the cases in which the sectional types of boiler are used.

As illustrating the general effect of increasing pressures, and the progressive diminution of the rate of gain, Mr. H. F. Smith has given the following tables of weight of steam and coal demanded per hour and per horse-power, by a perfect steam-engine, calculated on the assumption that 1100 thermal units per pound of coal are utilized by the boiler, which corresponds to an evaporation of about $11\frac{4}{10}$ parts by weight of water from and at the boiling-point, per one part of coal—a result attainable with good coal:

STEAM AND FUEL CONSUMPTION IN A PERFECT STEAM-ENGINE.

Boiler Pressure. Per Gauge.		Temperature.		Steam. Per I. H. P. per hour.				Coal. Per I. H. P. per hour.			
				Non-condensing.		Condensing.		Non-condensing.		Condensing.	
Lbs.	*Atmos.*	*Fahr.*	*Cent.*	*Lbs.*	*Kil.*	*Lbs.*	*Kil.*	*Lbs.*	*Kil.*	*Lbs.*	*Kil.*
300	20	421.7	216.5	10.48	4.8	6.16	2.7	0.98	.44	.64	.29
250	$16\frac{2}{3}$	405.9	207.7	11.19	5.1	6.39	2.9	1.04	.45	.66	.30
200	$13\frac{1}{3}$	387.6	197.5	12.16	5.5	6.68	3.0	1.13	.51	.69	.31
175	$11\frac{2}{3}$	377.1	191.7	12.81	5.7	6.87	3.1	1.18	.54	.71	.32
150	10	365.6	185.3	13.63	6.2	7.09	3.2	1.25	.57	.73	.33
125	$8\frac{1}{3}$	352.6	167.0	14.71	6.7	7.37	3.8	1.35	.60	.75	.34
100	$6\frac{2}{3}$	337.6	159.8	16.24	7.4	7.71	3.5	1.48	.67	.78	.35
90	6	330.9	166.1	17.05	7.7	7.89	3.6	1.55	.70	.80	.36
80	$5\frac{2}{3}$	323.6	162.0	18.03	8.2	8.09	3.7	1.64	.75	.82	.37
75	5	319.8	159.9	18.60	8.5	8.19	3.7	1.69	.77	.83	.38
70	$4\frac{2}{3}$	315.7	157.6	19.25	8.7	8.32	3.8	1.75	.80	.84	.39
60	4	307.1	152.8	20.83	9.5	8.59	3.9	1.88	.85	.87	.39
50	$3\frac{1}{3}$	297.5	147.5	22.95	10.4	8.92	4.1	2.07	.90	.90	.40
45	3	292.2	144.5	24.53	11.1	9.11	4.1	2.19	1.00	.91	.40

The table shows that at high pressures the gain of economy is very slow, and that the very best modern engines waste a large part of the steam passing through the cylinder. At 125 pounds, if there were no losses, *three fourths* of a pound of coal per hour would furnish one indicated horse-power, but very few engine-builders can be found who are willing to guarantee an indicated

horse-power with less than *one and three fourths* of a pound of coal per hour under the best of conditions.

A pound of coal, if all the heat were utilized, would evaporate 15 pounds of water from and at the boiling-point. Many boilers actually evaporate $11\frac{1}{4}$ pounds of water with an efficiency of 75 per cent.

An engine working perfectly would develop one indicated horse-power with $7\frac{5}{8}$ pounds of steam (of 125 pounds initial pressure) per hour; the best actual engines consume more than double this quantity.

Mr. G. H. Barrus gives the following as the probable actual steam-consumption of good engines:*

FEED-WATER CONSUMPTION FOR NON-CONDENSING ENGINES.

Initial pressure above atmosphere. Lbs.	Mean effective pressure. Lbs.	Feed-water consumed per I. H. P. per hour. Lbs.	Initial pressure above atmosphere. Lbs.	Mean effective pressure. Lbs.	Feed-water consumed per I. H. P. per hour. Lbs.
At 10 Per Cent Cut-off.			At 30 Per Cent Cut-off.		
40	1.32	153.24	40	16.95	33.52
50	5.01	52.52	50	23.71	29.35
60	8.70	37.26	60	30.47	27.24
70	12.39	30.99	70	37.21	25.76
80	16.07	27.61	80	43.97	24.71
90	19.76	25.43	90	50.73	23.91
100	23.45	23.90	100	57.49	23.27
At 20 Per Cent Cut-off.			At 40 Per Cent Cut-off.		
40	10.22	38.13	40	22.24	32.79
50	15.67	30.98	50	29.99	29.72
60	21.12	27.55	60	37.75	27.92
70	26.57	25.44	70	45.50	26.26
80	32.02	24.04	80	53.25	25.76
90	37.47	23.00	90	61.01	25.03
100	42.92	22.25	100	68.76	24.47
At 50 Per Cent Cut-off.					
40	26.40	33.16	80	60.44	26.99
50	34.91	30.53	90	68.96	26.32
60	43.42	28.94	100	77.48	25.78
70	51.94	27.79			

* The Tabor Indicator.

FEED-WATER CONSUMPTION FOR CONDENSING ENGINES.

Initial pressure above atmosphere. Lbs.	Mean effective pressure. Lbs.	Feed-water consumed per I. H. P. per hour. Lbs.	Initial pressure above atmosphere. Lbs.	Mean effective pressure. Lbs.	Feed-water consumed per I. H. P. per hour. Lbs.
AT 5 PER CENT CUT-OFF.			AT 20 PER CENT CUT-OFF.		
40	9.34	18.99	40	23.83	19.00
50	11.88	18.51	50	29.28	18.74
60	14.42	18.22	60	34.73	18.98
70	16.96	17.96	70	40.18	18.40
80	19.50	17.76	80	45.63	18.27
90	22.04	17.57	90	51.08	18.14
100	24.58	17.41	100	56.53	18.02
AT 10 PER CENT CUT-OFF.			AT 30 PER CENT CUT-OFF.		
40	14.96	18.25	40	30.54	20.57
50	18.65	17.91	50	37.30	20.35
60	22.34	17.68	60	44.06	20.19
70	26.03	17.47	70	50.81	20.04
80	29.72	17.30	80	57.57	19.91
90	33.41	17.15	90	64.32	19.78
100	37.10	17.02	100	71.08	19.67
AT 15 PER CENT CUT-OFF.			AT 40 PER CENT CUT-OFF.		
40	19.72	18.41	40	35.84	21.94
50	24.36	18.11	50	43.59	21.76
60	29.00	17.93	60	51.35	21.63
70	33.65	17.75	70	59.10	21.49
80	38.28	17.60	80	66.85	21.36
90	42.92	17.45	90	74.60	21.24
100	47.56	17.32	100	82.36	21.13

152. Safety and Efficiency vs. Cost may be taken as the most serious part of the problem to the designer and user of steam-boilers. The safety of the boiler being a first consideration, it becomes at once a question how far the engineer is justified in sacrificing money and special advantages to secure safety, and how closely he may be practically able to approximate absolute security. To increase strength of structure or of parts means to enlarge the dimensions, and to thus increase expense; to select a specially safe type, or peculiarly safe construction, is usually to meet the same objection; and it is soon found that there is a certain golden mean between maximum safety and impracticable expense which gives most satisfactory results. For ordinary cases, this is probably found not far from those proportions which give a "factor of safety" of about *six* for the important parts of the boiler, although good authori-

ties advise eight, and even ten, and general practice often falls to less than four.

The same difficulty arises when it is attempted to attain high efficiency. This must be done by extension of heating-surface and correspondingly increased first cost; and it is readily shown, as in Chapter XIII., that business considerations fix the limit of efficiency to be sought. This efficiency being given, the size and proportions of boiler become at once determinable. Thus accepting Rankine's formula for efficiency, already given in article 98, and taking the desired efficiency as given by calculation as E, the ratio of heating-surface divided by fuel burned, $\frac{\cancel{F}}{S} = R$, will be obtained thus: F.

$$E = \frac{B}{1 + AR;} \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (1)$$

$$R = \frac{B - E}{AE} \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (2)$$

Taking as common values $E = 0.70$, $A = 0.5$, $B = 1$,

$$R = \frac{0.30}{0.35} = 0.86 = \frac{F}{S}, \quad . \quad . \quad . \quad . \quad . \quad (3)$$

and the ratio of heating to grate-surface would be $S = \frac{F}{0.86}$; if $F = 15$, $S = 17.5$. Taking a rather high efficiency, $E = 0.80$, $R = 0.5$, and $S = 30$.

153. Water-tubes and Fire-tubes have, respectively, their own special advantages and disadvantages, and these differ in their importance in different types of boiler. It was shown by experiments directed by Engineer-in-chief B. F. Isherwood of the U. S. Navy,* that the water-tube boiler as constructed for marine purposes with vertical tubes is somewhat more economical than the horizontal fire-tube boiler of otherwise similar type, and the former excels in the perfection of its circulation and the readiness with which it can be freed from incrustation; it, however, makes a heavier boiler, and the

* Experimental Researches in Steam Engineering.

water-tube is less easily plugged if leaking. This latter difficulty, and the inconveniences and dangers arising from the accumulation of salt in marine boilers when water from injured tubes evaporates in the tube-box, have caused the disuse of this class of boilers. The "sectional" class of water-tube boilers is less subject to such objections.

Water-tubes are always set either vertical or steeply inclined, as horizontal or nearly horizontal water-tubes are liable to rapid destruction, and are comparatively inefficient because of the defective circulation invariably distinguishing them. The fire-tube may be used in any position, but is usually placed horizontally.

The general experience of engineers has been such as to lead them to adopt the water-tube in the so-called "safety" class of boilers and the fire-tube in others. The water-tube is usually placed at an angle, in these boilers, of about thirty degrees with the horizontal. In the "Field tube" the position is vertical, or nearly so; the lower end is closed, and an internal "circulating tube" permits the descent of a solid column of water while the mingled steam and water currents generated by the heat applied to the exterior of the main tube rise unobstructed to the surface.

Messrs. Porter and Allen found that water-tubes, closed at the bottom and set at an angle of about thirty degrees with the vertical, were capable of doing good work, and had a sufficiently good circulation to give extraordinarily high evaporative power. In all standard forms of "shell-boilers" the water-tubes are placed vertically, and are grouped in a low, long, and usually narrow tube-box, several of which tube-boxes are placed side by side in large boilers.

The fire-tube stands vertically in the common "upright" boiler, and is set horizontally, as has been seen in Chapter I., in all the other common forms.

As constructed by the best-known builders, the water-tube is expected to do about twenty per cent more work than the fire-tube of equal area. The water-tube shell-boiler is in some respects safer than the fire-tube boiler; since the water level can be carried below, and often a considerable distance below,

the top of the tube without endangering it. Low water with the horizontal fire-tube is always dangerous.

154. Shell and Sectional Boilers, compared in other respects than in reference to safety, in which attributes the latter are specially constructed to excel, are found, when equally well designed and constructed, and equally well managed, to stand on substantially the same level.

The two types of boiler in most common use are the water-tube sectional and the cylindrical fire-tube (shell) boiler. The latter is in the more extensive use, its cost, as a rule, being less, its regularity of steam-supply and uniformity of water-level greater, while its unity of structure, its convenience of access for inspection and repair, and perhaps more than all, the fact of its having a longer history, and being the product of a kind of survival of the fittest of the older types, giving it a hold upon the market that later forms of boiler have not secured. The former of these two classes has the grand advantage of safety against disruptive disastrous explosions, has equally good or better circulation and general efficiency, less weight and volume for equal powers, and greater reliability in its details of structure. Its joints are an objection, and its usually less steady operation is a disadvantage; but it is rapidly coming into favor among engineers, and into use as well.

The Author would often use the shell-boiler where commercial reasons would dictate such use, and, wherever practicable, would select the externally fired cylindrical fire-tube boiler, but would never place a shell-boiler under a building in which its explosion would endanger life or much property: the "safety" class of boiler would be the only form to be wisely adopted in such locations. Shell-boilers should usually be placed in detached boiler-houses, and so set, as to position, that danger shall be made a minimum, i.e., never pointing toward other buildings.

155. Natural and Forced Draught both have their advantages and their disadvantages. Chimney draught, unaided, gives a good supply of air to the fire, such as answers the purpose well for all ordinary work; is free from the objections

introduced with all machinery, and especially those arising from uncertainty of absolutely reliable continuous operation, and an equally certain expense for wear and tear. For the intense draught and large air-supply needed when a large amount of fuel is to be burned on a small area of grate, the size and especially the height of chimney required, and its cost, become serious matters, and for such cases a forced draught is the only suitable system.

There are two principal systems of forced draught, as already noted: that in which the air is forced directly into the ashpits through conduits leading from the fan or other source of the blast; and that in which the current is driven into the fire-room, or "stoke-hole," which is made air-tight for this purpose, and thence finds its way to the furnaces precisely as when a natural draught is adopted. Of these the first is the older and more common method; while the second is coming into use, particularly on torpedo-boats and elsewhere where enormously high rates of combustion are to be attained and kept up. By the older system the change from the forced to the natural draught is very conveniently made; but there is more difficulty in handling the fires, and the blowing of dust out into the room, and the danger of melting down the grate-bars, are two decided disadvantages, which are not inherent with the system involving the adoption of the air-tight fire-room. In the latter case the fires are as conveniently and nearly as comfortably managed as with natural draught; and as all air passes to the furnaces through the fire-room, if it is well directed, the ventilation and cooling of the room and the comfort of the men are comparatively well insured.

A later and in some respects most satisfactory system is that in which the air is drawn into the boiler-room by a fan placed as near the furnace as possible, and then forced through ducts into the ashpit, and into the interior of hollow furnace-doors in such manner as to intercept any gas that would otherwise be liable to find its way outward at the furnace mouth.

The Power required for Forced Draught is easily calculated thus:

Let p = pressure of blast per square foot;
w = weight of fuel burned per minute;
V_0 = volume of air per pound of fuel, at melting-point of ice;
T_0 = temperature, absolute, at 0° Fahr.;
T = " " of entering air;

C = coefficient of efficiency of blast apparatus.

Then the horse-power demanded will be

$$\text{H. P.} = \frac{pV_0wT}{33{,}000T_0C}.$$

Thus for 100 square feet of grate, at 60 pounds burned per hour or one pound per minute, per square foot, 200 cubic feet of air at 32° F. per pound of fuel, when $T_0 = 493.2$, $T = 532.2$, $C = \frac{1}{2}$, p = 3 inches of water = 16 pounds per square foot.

$$\text{H. P.} = \frac{16 \times 200 \times 1 \times 532.2}{33{,}000 \times 493.2 \times \frac{1}{2}} = 20 \text{ nearly.}$$

But good engines with such boilers should develop 2000 horse-power. The cost of blast would thus be about one per cent of the total power; while with natural draught the cost would probably be in vastly greater proportion in the form of waste heat.

An efficient water-circulation is very important, and the best boiler, as already stated, the most efficient as well as the safest, is that in which, other things being equal, the circulation is most complete, general, rapid, and steady. In nearly all boilers the circulation is a "natural" one; but occasionally, as in Pierce's rotary boiler,* as tested by the Author, and later at the U. S. Centennial Exhibition of 1876, and in the boiler of Professor Trowbridge, the circulation is a "forced" one. The last-named engineer made experiments,† assisted by Messrs. T. W. Mather and J. F. Klein, graduate students of the Shef-

* Reports on Steam-boilers at the U. S. Centennial Exhibition, 1876.

† Heat and Steam-engines, p. 146.

field Scientific School, to determine the efficiency of forced circulation. The difficulty of constructing very small steam-generators having sufficient strength to resist great pressure, and at the same time a high rate of evaporation with reasonable economy, has long been recognized. On account of this difficulty the use of very small engines is limited. The boiler in such engines must have such large proportions relatively to the engine that it ceases to be an economical apparatus.

The object of these experiments was to reduce the heating-surface, and at the same time make it more efficient by a forced and continuous circulation of the water in the boiler, through the means of a circulating pump. Various combinations and modes of circulation were tried, with results which appear conclusive. A steam-generator of very small volume and weight, made of coils of gas-pipe, and consequently having a resistance of several thousand pounds per square inch, was made to evaporate quantities of steam per hour which by ordinary processes would require a boiler of very much greater volume. The principle of forced circulation has not often been employed for this purpose, but there is reason to believe that it may become practically useful.

156. Special Conditions affecting Design thus arise in many cases, and may absolutely dictate the form of the boiler chosen and the place and method of its location and setting. Financial considerations often control; the matter of safety should always be kept in view, and may often be the deciding element in the problem. Peculiarities of location may, and often do, determine the size and form of the boiler to be chosen, and even the character of the feed-water will frequently decide such choice. No design is satisfactory except it meets in the most satisfactory manner practicable every element going to make up the whole problem, and is at the same time suitable for the location, the specific work to be done, and properly meets the pecuniary interests of those concerned, as well as gives the safest and most efficient arrangement possible under the circumstances.

157. The Chimney Draught, and the size, height, and general construction of chimney and flues, are among the first

of the details to be settled when preparing to design a steam-boiler.

The chimney draught is the first condition to be studied, since upon it primarily depends the power and performance of the boiler. The intensity of the draught in a well-proportioned chimney will vary nearly as the square root of its height. The quantity of fuel burned on the unit-area of grate is thus determined, assuming the chimney section properly proportioned to the work. The sectional area of the chimney-flue should be carefully proportioned to the maximum weight of fuel to be burned in the unit of time.

Chimneys are required to carry off obnoxious gases, and to produce a draught. Each pound of coal burned commonly yields from 15 to 50 pounds of gas, the volume of which varies directly as the absolute temperature.

The weight of gas carried off by a chimney in a given time depends upon size of chimney, velocity of flow, and density of gas. But as the density decreases directly as the absolute temperature, while the velocity increases, with a given height, nearly as the square root of the temperature, there is a temperature at which the weight thus delivered is a maximum, perhaps at twice the absolute temperature, or 550° above, the surrounding air. At 550° the quantity is *only four per cent* greater than at 300° above the ordinary temperature. Height and area are practically the only elements necessary to consider in an ordinary chimney.

The intensity of draught is independent of size, and varies directly with the product of the height into the difference of temperature.

The intensity of draught needed varies with the kind of fuel and the rate of combustion desired, being least for wood and other free-burning fuels, and greatest for the finer coals and "slack" or "brees," the latter requiring a chimney one hundred and fifty to two hundred feet high, and a difference of pressure measured by an inch or more of water.

The volume and weight of gas discharged from any furnace may be calculated as if it were of the density of air at the same temperature, the volume being 12½ cubic feet per pound, nearly,

at 0° F., or three fourths of a kilogram to the cubic metre. Adopting British measures, if V be the volume per pound at T, absolute, Fahrenheit degrees,

$$V = V_0 \frac{T}{T_0}; \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (1)$$

and we obtain, allowing, respectively, 12, 18, or 24 pounds to be equal to 150, 225, and 300 cubic feet, the following volumes of gases as originally calculated by Rankine:

VOLUMES OF GAS PER POUND OF FUEL IN CUBIC FEET. (RANKINE.)

T.	Air-Supply in Pounds per Pound of Fuel.		
	12	18	24
4640°	1551	..	..
3275°	1136	1704	..
2500°	906	1359	1812
1832°	697	1046	1395
1472°	588	882	1176
1112°	479	718	957
752°	369	553	738
572°	314	471	628
392°	259	389	519
212°	205	307	409
104°	172	258	344
68°	161	241	322
32°	150	225	300

If w denotes the weight of fuel burned in a given furnace *per second;*

V_0, the volume at 32° of the air supplied per pound of fuel;

T_1, the absolute temperature of the gas discharged by the chimney;

A, the sectional area of the chimney; then the velocity of the current in the chimney in feet per second is

$$u = \frac{wV_0T_1}{AT_0}; \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (2)$$

and the density of that current, in pounds to the cubic foot, is very nearly as in (3).

Since one cubic foot of air at the temperature T_0 weighs about 0.0807 pound, and the weight, on the assumption of uniform mean density of air and gases, is, at T_0, $0.0807 V_0 + 1$, and its mean density is

$$D_0 = \frac{0.0807 V_0 + 1}{V_0}, \text{ and at } T,$$

$$D = \frac{T_0}{T}\left(0.0807 + \frac{1}{V_0}\right). \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (3)$$

Multiplying D by the height of chimney, H, the weight of the column per unit section of its area, or, as here taken, in pounds on the square foot, becomes

$$p = Dh = \frac{T_0}{T} H\left(0.0807 + \frac{1}{V_0}\right); \quad . \quad . \quad . \quad . \quad (4)$$

or, expressed in inches of water,

$$p' = 0.19p = 0.19h\frac{T_0}{T}\left(0.0807 + \frac{1}{V_0}\right). \quad . \quad . \quad . \quad (5)$$

The *loss of head*, as found by Peclet,* may be expressed by the equation

$$h' = \frac{v^2}{2g}\left(13 + \frac{0.012l}{m}\right); \quad . \quad . \quad . \quad . \quad . \quad (6)$$

in which l is the total length of flue from grate to chimney-top, m its hydraulic mean depth, or area divided by perimeter, and v the velocity of flow in feet per second. When this head, h', is given we obtain

$$v = \sqrt{\frac{2gh'}{13 + \frac{0.012l}{m}}}; \quad . \quad . \quad . \quad . \quad . \quad . \quad (7)$$

* Traité de la Chaleur, vol. i.

and the weight of gas discharged must be

$$w = \frac{vA}{V_0} \cdot \frac{T_0}{T_1}; \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (8)$$

T_1 being the temperature of flue.

The head, h, producing flow is obviously the difference between the weight of chimney gases and that of the column of air of equal height outside; or, if T_2 is the temperature of the latter,

$$h = H\frac{T_1}{T_2} \cdot \frac{0.0807}{0.0807 + \frac{1}{V_0}} - H = H\left(0.96\frac{T_1}{T_2} - 1\right); \; . \quad (9)$$

$$H = h \div \left(0.96\frac{T_1}{T_2} - 1\right). \quad . \quad . \quad . \quad . \quad . \quad (10)$$

The velocity of flow is measured by $a\sqrt{h}$, a being a constant to be found by experiment, or by

$$v = a\sqrt{H}\sqrt{\left(0.96\frac{T_1}{T_2} - 1\right)}, \quad . \quad . \quad . \quad . \quad . \quad (11)$$

varying as the quantity $\sqrt{\left(0.96\frac{T_1}{T_2} - 1\right)}$; while the density varies as $1 \div T_1$, and the weight flowing per second varies as the product of velocity and density, or as $\frac{1}{T_1}\sqrt{(0.96T_1 - T_2)}$. This becomes a maximum, T_1 varying, as first indicated by Peclet,* when

$$\frac{du}{dx} = \frac{d\,\frac{\sqrt{0.96T_1 - T_2}}{T_1}}{dT_1} = 0 = \frac{2T_2}{0.96T_1} - 1, \quad . \quad (12)$$

and

$$\frac{T_1}{T_2} = \frac{2}{0.96} = 2.083, \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (13)$$

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* Peclet, vol. i. p. 166.

or, as Rankine states it,* $T_1 \div T_2 = \frac{25}{12}$, nearly; and the most effective draught, but not the most economical, is obtained when the absolute temperature of the flue-gases is 2.08 times that of the atmosphere, or about 550° Fahr. (288° Cent.), provided the conditions of grate-resistance are as here assumed. For maximum efficiency of apparatus and economy of fuel the temperature must be made as low as possible.

In constructing grates for boilers the air-spaces should be made as narrow as is practicable, the bituminous coals requiring more air-space than anthracite. A half-inch is usually considered a minimum and three fourths a maximum. The area of grate should be somewhat more for wood than for coal, the same power being demanded.

158. The Size and Design of the Chimney, its height and area of flue, are modified somewhat by its form and proportions, and by the character of its interior surfaces. The greater the friction-head the less its effectiveness. A chimney of circular section and with a straight uniform flue is better than with any other section or with less direct flue. The flue-area is either uniform or tapering toward the top, in which latter case the area for calculations is measured at the top. Mr. Kent assumes that the friction may be taken as equivalent to a reduction of section of two inches all around, and a square flue section as equivalent to a circular one of diameter equal to its side.† He thus obtains the following: Assuming a commercial horse-power to demand the consumption of 5 pounds of coal per hour, we have the following formulæ:

$$E = \frac{0.3\,HP}{\sqrt{H}} = A - 0.6\sqrt{A}; \quad \dots \quad (1)$$

$$HP = 3.33\,E\sqrt{H}; \quad \dots \quad (2)$$

$$s = 12\sqrt{E} + 4; \quad \dots \quad (3)$$

$$d = 13.54\sqrt{E} + 4; \quad \dots \quad (4)$$

$$H = \left(\frac{0.3HP}{E}\right)^2; \quad \dots \quad (5)$$

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increases. See On Chimney Draught, by the Author, Trans. Am. Soc. M. E., 1890.

† Trans. Am. Soc. M. E., 1884.

in which HP = horse-power; H = height of chimney in feet; E = effective area, and A = actual area in square feet; S = side of square chimney, and d = dia. of round chimney in inches. The following table* is calculated by means of these formulæ:

SIZES OF CHIMNEYS AND HORSE-POWER OF BOILERS.

Dia. in inches.	Height of Chimneys, and Commercial Horse-Power.											Side of square inches.	Eff'tive Area. sq. feet.	Actual Area. sq. feet.
	50 ft	60 ft	70 ft.	80 ft.	90 ft.	100 ft.	110 ft.	125 ft.	150 ft.	175 ft.	200 ft.			
18	23	25	27	..	..	..	..	..	..	..	..	16	0.97	1.77
21	35	38	41	..	..	..	..	..	..	..	..	19	1.47	2.41
24	49	54	58	62	..	..	..	..	..	..	..	22	2.08	3.14
27	65	72	78	83	..	..	..	..	..	..	..	24	2.78	3.98
30	84	92	100	107	113	..	..	..	..	.	..	27	3.58	4.91
33	..	115	125	133	141	..	..	.	..	..	..	30	4.48	5.94
36	..	141	152	163	173	182	..	..	..	..	..	32	5.47	7.07
39	..	..	183	196	208	219	..	..	..	..	..	35	6.57	8.30
42	..	..	216	231	245	258	271	..	..	..	..	38	7.76	9.62
48	..	..	..	311	330	348	365	389	..	..	..	43	10.44	12.57
54	..	..	..	..	427	449	472	503	551	..	..	48	13.51	15.90
60	..	..	..	..	536	565	593	632	692	748	..	54	16.98	19.64
66	..	..	..	..	..	694	728	776	849	918	981	59	20.83	23.76
72	..	..	..	..	..	835	876	934	1023	1105	1181	64	25.08	28.27
78	..	..	..	..	..	..	1038	1107	1212	1310	1400	70	29.73	33.18
84	..	..	..	..	..	..	1214	1294	1418	1531	1637	75	34.76	38.48
90	..	..	..	..	..	..	..	1496	1639	1770	1893	80	40.19	44.18
96	..	..	..	..	..	..	..	..	1876	2027	2167	86	46.01	50.27

The external diameter at the base should be one tenth the height, unless it be supported by some other structure. The "batter" or taper of a chimney should be from $\frac{3}{16}$ to $\frac{1}{4}$ inch to the foot on each side.

The thickness of brick-work should be, usually, one brick (8 or 9 inches) for 25 feet from the top, increasing $\frac{1}{2}$ brick (4 or $4\frac{1}{2}$ inches) for each 25 feet from the top downwards. If the inside diameter exceed 5 feet the top length should be $1\frac{1}{2}$ bricks, and if under 3 feet it may be $\frac{1}{2}$ brick for ten feet.

To find the maximum draught for any given chimney, the heated column being 612° F., and the external air 62°:

Multiply the height above grate in feet by .0075, *and the product is the draught-power in inches of water.*

For natural draught it is found that the weight in pounds of anthracite coal which can be burned on the square foot of grate per hour is, as a maximum, for example, under the best conditions in marine boilers,

* "Power," 1885.

$$F = 2\sqrt{H} - 1, \text{ nearly}; \quad \ldots \ldots \quad (6)$$

and, under more ordinary conditions,

$$F = 1.5\sqrt{H} - 1. \quad \ldots \ldots \quad (7)$$

From this we obtain the following:

HEIGHTS OF CHIMNEY AND RATES OF COMBUSTION.

Chimney-section = $\frac{1}{7}$ to $\frac{1}{8}$ grate-area.

Fuel, Anthracite.	*Best Conditions.*
$H = \dfrac{(W+1)^2}{4}$;	$W = 2\sqrt{H} - 1.$

H = height of chimney in feet; W = weight of coal burned per square foot of grate per hour.

Thus for

$$\begin{aligned} H &= 50, & W &= 13; \\ H &= 65, & W &= 15; \\ H &= 80, & W &= 17; \\ H &= 100, & W &= 19. \end{aligned}$$

These figures represent very exactly the results of Isherwood's experiments* with anthracite coals.

The best Welsh and Maryland semi-anthracites, or good bituminous and semi-bituminous coals, should give, as maxima,

$$F = 2.25\sqrt{H},$$

and the less valuable soft coals, more nearly

$$F = 3\sqrt{H}.$$

Thus, average coals of each quality stand, relatively, nearly as follows:

	Weight per Sq. Foot Grate.	Area Grate per Pound.
Good anthracite coals	1.00	1.0
" semi-anthracite and bitum.	1.05	0.9
Ordinary low-grade coals, soft	1.5	0.7
" " " anthracite	0.9	1.1

* Trowbridge, Heat and Heat-engines, N. Y., 1874; Isherwood, Researches in Engineering (1860).

Some of the soft coals will burn still more freely, while some anthracites will burn even less rapidly than above stated. The figures given may be taken as fair averages. The height of chimney being known in advance or settled upon, the total quantity of fuel to be burned determines the area of grate. This total quantity is known from the chemical constitution of the fuel, or by experiment under defined conditions, and from the work demanded and the intended efficiency of the boiler, as estimated by the methods already described.

Mr. Lowe, a builder of large experience, finds the following good proportions* for stationary boilers, presumably allowing about 30 pounds of water per hour, and 15 square feet of heating-surface per horse-power:

STEAM-BOILER CHIMNEYS.

Heights in feet	50	60	70	80	90	100
Sq. in. area per H.P.	9	8.67	8.34	8.01	7.68	7.35
Heights in feet	110	120	130	140	150	
Sq. in. area per H.P.	7.02	6.69	6.36	6.03	5.70	
Heights in feet	160	170	180	190	200	
Sq. in. area per H.P.	5.37	5.04	4.71	4.38	4.05	

Professor C. A. Smith† gives the following formulas for the relation of height of chimney to fuel consumption:

$$H=\left(\frac{5F}{A}\right)^2; \qquad A=\frac{5F}{\sqrt{H}}; \qquad F=\tfrac{1}{5}A\sqrt{H};$$

where H is the height of chimney in feet, A its flue-section in square feet, and F the pounds of coal burned per minute.

Mr. J. T. Henthorn‡ gives the following tables of dimensions of chimney as obtained by the empirical formula:

$$\frac{120\,G}{\sqrt{H}}=A;$$

in which he takes the area, G, of grate in square feet, the height, H, in feet, and the area of flue, A, in inches. It is

* *Am. Machinist*, March 27, 1886.

† *Am. Engineer*, Sept. 21, 1883, p. 123.

‡ *Journal of Commerce*, July 5, 1884.

AREAS OF CHIMNEY-FLUE (in Square Inches).

Heights of Chimney in Feet.

Square ft. of Grate Surface.	60	65	70	75	80	85	90	95	100	105	110	115	120	125	130	135	140	145	150	155	160	Square ft. of Grate Surface.
25	387	372	358	346	335	325	316	307	300	292	286	......	......	......	......	......	......	......	......	......	......	25
50	774	744	717	692	670	650	632	615	600	585	572	......	......	......	......	......	......	......	......	......	......	50
75	1,161	1,116	1,055	1,039	1,006	976	948	923	900	878	858	839	......	......	......	......	......	......	......	......	......	75
100	1,549	1,488	1,434	1,385	1,341	1,301	1,264	1,231	1,200	1,171	1,144	1,119	......	......	......	......	......	......	......	......	......	100
125	1,936	1,860	1,792	1,732	1,677	1,626	1,581	1,538	1,500	1,463	1,430	1,398	1,369	......	......	......	......	......	......	......	......	125
150	2,323	2,232	2,151	2,078	2,012	1,952	1,897	1,846	1,800	1,756	1,716	1,678	1,643	1,609	......	......	......	......	......	......	......	150
175	2,711	2,604	2,509	2,424	2,347	2,277	2,213	2,154	2,100	2,049	2,002	1,958	1,917	1,878	1,841	......	......	......	......	......	......	175
200	3,098	2,976	2,868	2,771	2,683	2,603	2,529	2,462	2,400	2,342	2,288	2,238	2,190	2,146	2,104	2,065	......	......	......	......	......	200
225	3,485	3,348	3,227	3,117	3,018	2,928	2,846	2,770	2,700	2,634	2,574	2,517	2,464	2,314	2,368	2,323	......	......	......	......	......	225
250	3,873	3,721	3,585	3,464	3,354	3,253	3,162	3,077	3,000	2,927	2,860	2,797	2,738	2,683	2,631	2,582	2,535	2,491	......	......	......	250
275	4,260	4,093	3,944	3,810	3,689	3,579	3,478	3,385	3,300	3,220	3,146	3,077	3,012	2,951	2,894	2,840	2,789	2,740	......	......	......	275
300	4,647	4,465	4,302	4,157	4,024	3,904	3,794	3,693	3,600	3,513	3,432	3,257	3,286	3,219	3,157	3,098	3,042	2,989	2,939	......	......	300
325	5,034	4,837	4,661	4,503	4,360	4,230	4,110	4,001	3,900	3,801	3,718	3,636	3,560	3,488	3,420	3,356	3,296	3,238	3,184	3,132	......	325
350	5,422	5,209	5,019	4,849	4,695	4,555	4,427	4,309	4,200	4,098	4,004	3,916	3,834	3,756	3,683	3,614	3,549	3,487	3,429	3,373	3,320	350
375	......	5,581	5,378	5,196	5,031	4,880	4,743	4,616	4,500	4,391	4,290	4,196	4,107	4,024	3,946	3,873	3,803	3,737	3,674	3,614	3,557	375
400	......	......	5,737	5,542	5,366	5,206	5,059	4,924	4,800	4,684	4,576	4,476	4,381	4,293	4,209	4,131	4,056	3,986	3,919	3,855	3,794	400
425	......	......	......	5,889	5,702	5,531	5,375	5,232	5,100	4,977	4,862	4,755	4,655	4,561	4,473	4,389	4,310	4,235	4,164	4,096	4,031	425
450	......	......	......	......	6,037	5,857	5,692	5,540	5,400	5,269	5,148	5,035	4,929	4,829	4,736	4,647	4,563	4,484	4,409	4,337	4,269	450
475	......	......	......	......	6,372	6,182	6,008	5,848	5,700	5,562	5,434	5,315	5,203	5,098	4,999	4,905	4,817	4,733	4,654	4,578	4,506	475
500	......	......	......	......	......	6,507	6,324	6,155	6,000	5,855	5,720	5,595	5,477	5,366	5,262	5,164	5,070	4,982	4,899	4,819	4,743	500
525	......	......	......	......	......	6,832	6,640	6,463	6,300	6,148	6,006	5,874	5,751	5,634	5,525	5,422	5,325	5,231	5,143	5,060	4,980	525
550	......	......	......	......	......	7,158	6,957	6,771	6,600	6,440	6,292	6,154	6,024	5,903	5,788	5,680	5,578	5,481	5,388	5,301	5,217	550
575	......	......	......	......	......	......	7,273	7,079	6,900	6,733	6,578	6,434	6,298	6,171	6,051	5,938	5,831	5,730	5,633	5,542	5,454	575
600	......	......	......	......	......	......	7,389	7,387	7,200	7,026	6,861	6,714	6,572	6,439	6,314	6,169	6,085	5,979	5,878	5,783	5,692	600
625	......	......	......	......	......	......	7,905	7,694	7,500	7,319	7,151	6,993	6,846	6,708	6,577	6,455	6,338	6,228	6,123	6,024	5,929	625
650	......	......	......	......	......	......	8,221	8,002	7,800	7,612	7,437	7,273	7,120	6,976	6,841	6,713	6,592	6,477	6,368	6,265	6,166	650
675	......	......	......	......	......	......	......	8,310	8,100	7,904	7,723	7,553	7,394	7,244	7,104	6,971	6,845	6,726	6,613	6,506	6,403	675
700	......	......	......	......	......	......	......	8,618	8,400	8,197	8,009	7,833	7,668	7,513	7,367	7,229	7,099	6,975	6,858	6,747	6,640	700
725	......	......	......	......	......	......	......	8,926	8,700	8,490	8,295	8,112	7,942	7,781	7,630	7,487	7,352	7,225	7,103	6,988	6,877	725
750	......	......	......	......	......	......	......	9,233	9,000	8,783	8,581	8,392	8,215	8,049	7,893	7,746	7,606	7,474	7,348	7,229	7,115	750
775	......	......	......	......	......	......	......	9,540	9,300	9,075	8,867	8,672	8,489	8,318	8,156	8,004	7,859	7,723	7,593	7,469	7,352	775
800	......	......	......	......	......	......	......	......	9,600	9,368	9,153	8,952	8,763	8,586	8,419	8,262	8,113	7,972	7,838	7,710	7,589	800
825	......	......	......	......	......	......	......	......	9,900	9,661	9,439	9,231	9,037	8,854	8,682	8,520	8,367	8,221	8,083	7,951	7,826	825
850	......	......	......	......	......	......	......	......	10,200	9,054	9,725	9,511	9,311	9,123	8,946	8,778	8,620	8,470	8,328	8,192	8,063	850
875	......	......	......	......	......	......	......	......	10,500	10,246	10,011	9,791	9,585	9,391	9,209	9,037	8,874	8,719	8,573	8,433	8,300	875
900	......	......	......	......	......	......	......	......	10,800	10,539	10,297	10,071	9,859	9,659	9,472	9,295	9,127	8,968	8,818	8,674	8,538	900
925	......	......	......	......	......	......	......	......	11,100	10,832	10,583	10,350	10,132	9,928	9,735	9,553	9,381	9,218	9,063	8,915	8,775	925
950	......	......	......	......	......	......	......	......	11,400	11,125	10,869	10,630	10,406	10,196	9,998	9,811	9,634	9,467	9,308	9,156	9,012	950
975	......	......	......	......	......	......	......	......	11,700	11,418	11,155	10,910	10,680	10,464	10,261	10,069	9,888	9,716	9,553	9,397	9,249	975
1000	......	......	......	......	......	......	......	......	12,000	11,710	11,441	11,190	10,954	10,733	10,524	10,328	10,141	9,965	9,798	9,638	9,486	1000

GENERAL DIMENSIONS OF CHIMNEY.

Height in Feet.	60	70	80	90	100	110	120	130	140	150	160
Horse-power=Grate-surface × 3	75	93	112.5	168	240	375	564	843	1260	1875	3000
Grate-surface connected	25	31	37.5	56	80	121	188	281	420	625	1000
Diameter of inside of flue at base	22¼ in.	22¾ in.	25¼ in.	30 in.	35 in.	42¾ in.	51¼ in.	61¼ in.	73¾ in.	88¼ in.	110 in.
Diameter of inside of flue at top	22¼ in.	22¾ in.	25¼ in.	30 in.	35 in.	42¾ in.	51¼ in.	61¼ in.	73¾ in.	88¼ in.	110 in.
Size of outside wall at base—square	76¼ in.	81¾ in.	89¼ in.	99 in.	109 in.	121¾ in.	135¼ in.	150¼ in.	167¾ in.	187¼ in.	214 in.
Size of outside wall at top—square	46¼ in.	46¾ in.	49¼ in.	54 in.	59 in.	66¾ in.	75¼ in.	85¼ in.	97¾ in.	112¼ in.	134 in.
Ratio of base to height	9.44	10.27	10.78	10.90	11	10.84	10.64	10.38	10.01	9.60	8.97
Batter per foot each side	¼ in.	¼ in.	¼ in.	¼ in.	¼ in.	¼ in.	¼ in.	¼ in.	¼ in.	¼ in.	¼ in.
Total batter on each side	15 in.	17½ in.	20 in.	22½ in.	25 in.	27½ in.	30 in.	32½ in.	35 in.	37½ in.	40 in.
Size of outside wall measured inside at bottom	60¼ in.	65¾ in.	65¼ in.	75 in.	85 in.	89¾ in.	103¼ in.	110¼ in.	127¾ in.	139¼ in.	166 in.
Size of outside wall measured inside at top	30¼ in.	30¾ in.	33¼ in.	38 in.	43 in.	50¾ in.	59¼ in.	69¼	81¾ in.	96¼ in.	118 in.
Number of projections in outside wall	0	0	1	1	1	2	2	3	3	4	4
Height to first projection	60 ft.	70 ft.	40 ft.	45 ft.	50 in.	34 ft.	40 ft.	33 ft.	35 ft.	30 ft.	32 ft.
Thickness of wall	8 ft.	8 in.	12 in.	12 in.	12 in.	16 ft.	16 ft.	20 ft.	20 ft.	24 in.	24 in.
Height from first to second projection	....	....	40 in.	45 in.	50 in.	34 ft.	40 ft.	33 ft.	35 ft.	30 ft.	32 ft.
Thickness of wall	....	....	8 ft.	8 in.	8 in.	12 ft.	12 in.	16 in.	16 in.	20	20 ft.
Height from second to third projection	....	....	....	....	....	32 ft.	40 ft.	33 ft.	35 ft.	30 ft.	32 ft.
Thickness of wall	....	....	....	....	....	8 in.	8 in.	12 in.	12 in.	16 in.	16 in.
Height from third to fourth projection	....	....	....	....	....	....	....	31 ft.	35 ft.	30 ft.	32 ft.
Thickness of wall	....	....	....	....	....	....	....	8 in.	8 in.	12 in.	12 in.
Height from fourth projection to top	....	....	....	....	....	....	....	....	....	30 ft.	32 ft.
Thickness of wall	....	....	....	....	....	....	....	....	....	8 in.	8 in.
Number of projections in inside wall or lining	2	2	2	2	2	2	2	3	3	3	3
Height to first projection	30 ft.	34 ft.	39 ft.	44 ft.	49 ft.	54 ft.	59 ft.	43 ft.	46 ft.	49 ft.	53 ft.
Thickness of wall	8 in.	8 in.	8 in.	8 in.	8 in.	8 in.	8 in.	12 in.	12 in.	12 in.	12 in.
Height from first to second projection	28 ft.	34 ft.	39 ft.	44 ft.	49 ft.	54 ft.	59 ft.	43 ft.	46 ft.	49 ft.	53 ft.
Thickness of wall	4 in.	4 in.	4 in.	4 ft.	4 in.	4 in.	4 in.	8 in.	8 in.	8 in.	8 in.
Height from second projection to top	....	....	....	....	....	....	....	42 ft.	46 ft.	50 ft.	52 ft.
Thickness of wall	....	....	....	....	....	....	....	4 in.	4 in.	4 in.	4 in.

assumed, as in common practice, that the plain cylindrical boiler on an average will, when supplying a good engine with detachable valve-gear, require about 4.7 square feet of heating-surface for actual indicated horse-power, and the tubular boiler 11.8, the two boilers giving 2.1 and 3 horse-power, respectively, per square foot of grate.

The following figure is the graphic representation of the

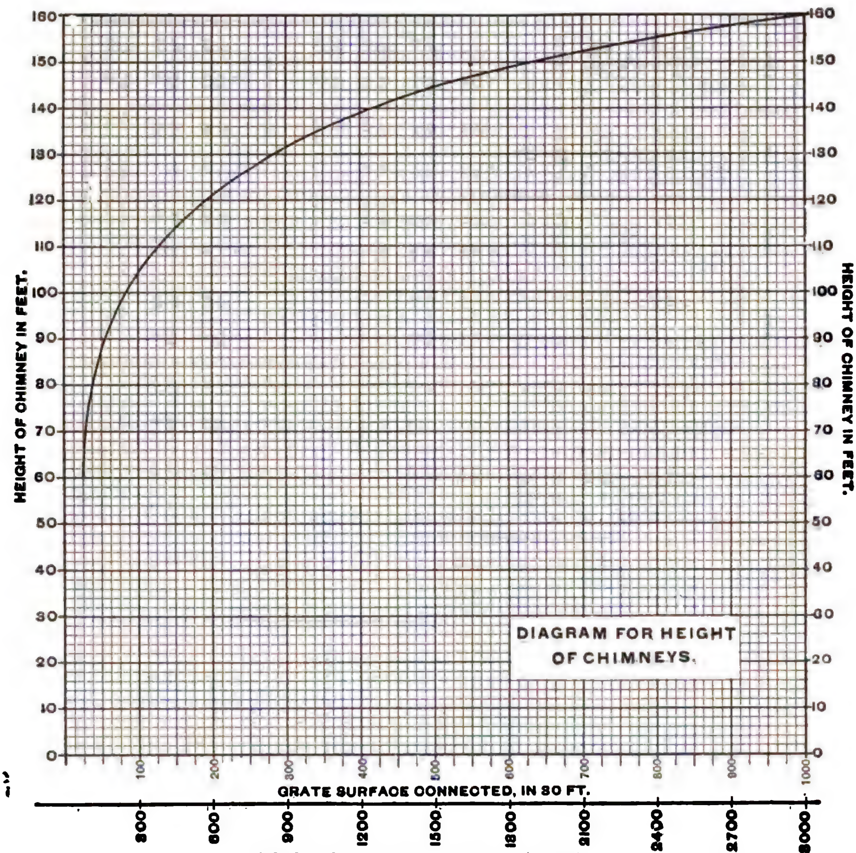

FIG. 73.—DIMENSIONS OF CHIMNEY.

law of variation of height with power required or size of boiler, as algebraically given in the formula above.

In building the chimney for ordinary use in connection

with steam-boilers, the fire-brick lining needed, at its lower part, when receiving gases from metallurgical or mill furnaces, is not required. The centre-line is fixed on the ground and preserved vertical, while under construction, by the use of a "plumb-line," preferably of fine brass wire, with a very heavy "bob" steadied by immersion in a pail of water, molasses, or other liquid.

The shell should rarely be less in thickness than the length of a brick at the top, and the lining not less than one half that thickness; this thickness, outside, should be increased by the width of a brick at every interval of 50 or 60 feet from the top, the lining being kept approximately, as near as may be, at one half the thickness of the main wall.

The great chimney at St. Rollox, Glasgow, of the height of 455½ feet, has the following dimensions:

Division of the Chimney.	Height above Ground.	Outer Diameter in Feet.	Thickness of the Wall in	
			Feet	and Inches.
	435½	13½		
V.			1	2
	350½	16¾		
IV.			1	6
	210½	24		
III.			1	10½
	114½	30½		
II.			2	3
	54½	35		
I.			2	7½
	0	40		

The foundation of this chimney has a depth of 20 feet and a diameter of 50 feet. It has stood safely and has worked satisfactorily for nearly a half-century, and may be looked upon as a good example of successful construction.

159. Forms and Proportions of Furnace and Grate are settled upon so soon as the character of the fuel and the proportions of chimney are fixed.

The rate of combustion is fixed, as a maximum, as already seen, by the height of chimney; minimum rates are anything

less, and the customary rates may be taken as not far from the following.

The rate of combustion of coal in a furnace is usually stated in pounds per hour, burned on each square foot of grate.

WITH CHIMNEY-DRAUGHT.	Pounds per square foot per hour.
1. The slowest rate of combustion in Cornish boilers....	4 to 6
2. Ordinary rate in these boilers........................	10 to 15
3. Ordinary rates in factory boilers	12 to 18
4. Ordinary rates in marine boilers.....................	15 to 25
5. Quickest rates of complete combustion of anthracite coal, the supply of air coming through the grate only	15 to 20
6. Quickest rates of complete combustion of bituminous coal, with air-holes above the fuel $\frac{1}{16}$ the area of grate..	20 to 25
FORCED DRAUGHT.	
7. Locomotives..	40 to 100
8. Torpedo-boats......................................	60 to 125

Fuels of the several classes should evaporate, respectively, from feed-water at the boiling-point and at atmospheric pressure, under the most favorable possible conditions, about as follows:

	Relatively.	Weight water per unit weight of fuel.
Best anthracite......................	100	13.5
Best semi-anthracite and bituminous..	110	15
Ordinary coals, soft..................	80	11
Ordinary coals, anthracite............	75	10

Examples of these several classes are seen in the best Pennsylvania anthracites, the Welsh and Maryland semi-anthracites, or semi-bituminous coals, the ordinary good bituminous fuels of Nova Scotia and of Western Pennsylvania, and the earthy coals of the West.

The quantity of steam actually made will depend upon the temperature of the feed-water, and will be less as the water is colder. It is customary, as elsewhere stated, to reduce the results of experiments determining efficiency of boilers to

"equivalent evaporation from and at the boiling-point," under atmospheric pressure.

When the maximum possible evaporation is given for feed at 212° F. (100° C.), and at atmospheric pressure, i.e., under the standard conditions, multiplying that figure by the reciprocal of the factor of evaporation for the proposed temperatures of feed and of steam will give the maximum possible evaporation under the latter conditions. Thus we get the following:

RELATIVE EVAPORATION AT VARYING TEMPERATURES OF FEED.

Temperature of feed-water.....	212° F.	200	180	160	140	120	100	80	60	40
	100° C.	93.3	82.2	71.1	60.0	48.8	37.7	26.6	15.5	4.4
Relative steam evaporation....	100	98	96	94	92	90	88	87	86	84

The coals in common use in the United States are:

The semi-bituminous coals from Maryland.
The anthracites from Pennsylvania.
The bituminous coals from Pittsburg and Western Pennsylvania.
The bituminous coals from Ohio and the West.

When burned in ordinary furnaces, these coals will make steam, per pound of coal, in nearly the following proportions, as given by Mr. T. Skeel:*

Semi-bituminous	110
Anthracite	100
Pittsburg	90
Ohio	75

The weights that may be burned on the same grate, with the same chimney, will vary nearly as follows:

Anthracite	100
Semi-bituminous	120
Pittsburg	120
Ohio	200

Relative areas of grate-surface that will be necessary to burn coal enough to furnish the same quantity of steam are nearly as follows:

* Weisbach, Vol. II.

Anthracite	100
Pittsburg	90
Semi-bituminous	75
Ohio	67

This refers to the average coal of each kind in practice.

The loss as refuse falling through well-proportioned grate-bars may be taken as 5 to 10 per cent for good bituminous coals, or 10 to 20 per cent for the lower grades, and about the same for anthracites. Wood may be taken by weight as having one half the value of coal. A cord of best hard wood should equal a ton of good coal.

From the results of chemical analyses, the evaporative power of various kinds of fuel, expressed in pounds of water per pound of fuel evaporated from and at 212° F., which we will call E, has average values given by Prof. C. A. Smith* in the following table, which may be found useful, as supplementary to the several other sets of data already given in this connection.

Kinds of Fuel.	*E*
Pure carbon completely burned to CO_2	15
Pure carbon incompletely burned to CO	4.5
CO completely burned to CO_2	10.5
Charcoal from wood, dry	14
Charcoal from peat, dry	12
Coke good, dry	14
Coke average, dry	13.2
Coke poor, dry	12.3
Coal, anthracite	15.3
Coal, dry bituminous, best	15.9
Coal, bituminous	14
Coal, caking, bituminous, best	16
Coal, Illinois (from four mines near St. Louis)	12
Lignite	12.1
Peat, dry	10
Peat with one fourth water	7.5
Wood, dry	7.25
Wood with one fifth water	5.8
Wood, best dry pitch-pine	10
Mineral oils, about	22.6

* *Am. Engineer*, 1883.

The anthracite coals burn completely with a thin fire and excess of air, but should have a thickness pretty nearly proportional to the rate of combustion, a good proportion being about one foot thickness on a rate of combustion of 20 pounds on the square foot of grate per hour (1 decimetre per 65 kilogs. on the square metre). The bituminous coals will not burn well except in a thick bed and at high temperature, and when removed from the chilling influence of adjacent cold iron. A hot fire and large space for combustion are here essential. The furnace may therefore be of less capacity with hard than with soft coals; but a good height over the grate and a large combustion-chamber are very desirable with the latter, and are of advantage in all cases. A fire-brick furnace, or an arch of brick-work over the grate, gives some gain usually.

The rate of combustion to be anticipated and the intended efficiency of boiler, and evaporation per unit weight of fuel being ascertained, the area of grate is at once calculable by dividing the total weight of steam to be supplied by the evaporation to obtain the weight of fuel to be needed, and then dividing this total weight per unit of time by the quantity to be burned on a unit area of grate. Thus, 1000 horse-power being called for, at 30 pounds (13.6 kilogs.) per H. P. per hour, 30,000 pounds (1361 kilogs.) of steam are demanded per hour. At 10 pounds' evaporation and 10 pounds burned on the square foot (48.8 kilogs. on the square metre) of grate-surface, 300 square feet (27.9 square metres) of grate must be provided, which would usually be divided, for convenience in construction and operation, between several furnaces, as furnaces of greater depth than about 6 feet (1.8 m.) cannot be easily handled, that being about as far as coal can be well thrown; while a greater width than 3 or 4 feet (0.9 to 1.2 m.) introduces difficulties of construction.

The "combustion-chamber," which usually forms a part of a well-designed furnace, may be either simply an enlargement of the height of the furnace itself to obtain the space and time needed by the gas-currents for complete intermixture and thorough combustion, or it may be any separate chamber beyond the grate. The latter is often the best method of securing the

desired results; but the more usual plan is that of giving considerable height of furnace-crown.

Grate-bars are spaced differently for different kinds of fuel. Thus, for fine "pea" anthracite coal, the spaces between the bars are usually made about a quarter of an inch (0.6 cm.); for "chestnut," $\frac{3}{8}$ inch (0.9 cm.); for "stove" coal, $\frac{1}{2}$ inch (1.27 cm.); and for large anthracite and for bituminous coals, $\frac{3}{8}$ to $\frac{3}{4}$ inch (0.95 to 1.9 cm.); while wood-burning calls for an inch (2.56 cm.).

160. The Relative Areas of Chimney, Flues, and Grate are seen to be variable with the circumstances under which the boiler is to be operated, but with natural draught and usual working conditions certain proportions have become almost universally accepted as standard in common practice. Thus it may be taken as well settled by experience, that in chimneys of circular section, smooth internal surfaces, and in the open, where draught is unobstructed by air-currents produced by surrounding objects, as, for example, with marine steam-boilers, the minimum ratio of chimney-flue section, section through the tubes and that over the bridge-wall to grate-surface should be, at least, respectively, $\frac{1}{9}$, $\frac{1}{8}$, $\frac{1}{7}$, while a maximum to be adopted with forced draught is not far from $\frac{1}{7}$, $\frac{1}{6}$, and $\frac{1}{6}$, for anthracite coal. The latter ratios will also work well for bituminous, free-burning, coals and natural draught; and the sections may often be made still greater, with advantage when a blast is also used with such fuel.

With restricted draught-area the amount of fuel that may be burned becomes reduced; thus, assuming a chimney 50 feet (16 m.) high:

Area of least flue-section (grate = 1) ...	0.14	0.10	0.07	0.05	0.04
Relative coal burned..................	1.	0.8	0.7	0.6	0.4
Average fuel, lbs. per sq. ft. grate......	15	12	10	9	6
" " kilogs. per sq. m.........	7.5	6	5	4.5	3

For square sections of chimney-flue and with rough interior surfaces the size of chimney is increased both in weight and area of section. As a general rule, the height of factory chimneys is increased with the size and number of boilers, irrespec-

tive of the above-stated ratios, and a not uncommon proportion of "stack" is that which makes the height about twenty times the diameter of the flue. Ordinary mill-chimneys, for moderate powers, range between 50 and 75 feet (16 and 23 m.) in height.

161. Common Proportions of Boiler are found in ordinary practice to be not far from those given below.

The interior space of the boiler is commonly divided into about two thirds or three fourths water-space, the remainder being steam-room. In marine boilers more steam-space should be given.

RATIO OF HEATING TO GRATE SURFACE.

Plain cylinder boilers	12 to 15
Cornish	15 to 30
Cylindrical flue	20 to 25
" tubular	25 to 35
Marine tubular (fire)	30 to 35
" " (water)	35 to 40
Locomotive tubular	50 to 100

The ratio of heating to grate surfaces should, where possible, be always carefully determined with reference to maximum commercial efficiency in the manner described in a later chapter.

The above proportions produce ratios of weights of fuel burned per unit area of heating-surface, in general practice, about as follows:

RATIO OF FUEL BURNED TO HEATING-SURFACE.

	Pounds per sq. ft. H. S.	Kilogs. per sq. in.
Stationary boilers	0.5 to 1.0	0.1 to 0.2
Marine (natural draught)	0.5 to 0.6	0.1 to 0.3
Locomotive and forced draught	0.8 to 1.0	0.4 to 0.5

Similarly, the power of such boilers may be reckoned roughly as below, and their relative standing in efficiency and capacity taken as follows:

HORSE-POWER AND ECONOMY.

	Per H. P.		Relative Standing.	
	Sq. ft.	Sq. m.	Capacity.	Economy.
Water-tube..................	10 to 12	1.0 to 1.1	1.	1.
Fire-tube....................	14 to 18	1.3 to 1.6	0.75	0.9
Flue.........................	8 to 12	0.7 to 1.1	0.50	0.8
Plain cylindrical............	6 to 10	0.5 to 0.9	0.20	0.7
Locomotive...................	1 to 2	0.1 to 0.2	0.6	0.8

The above, as with every proportion and detail of the steam-boiler, should always be made the subject of careful calculation whenever the case is in the least degree peculiar.

The following are proportions frequently accepted by the trade in one of the most common varieties of stationary boiler sold in the market:

PROPORTIONS OF CYLINDRICAL TUBULAR BOILERS.

Number of Size.	Horse-power.	Diameter—inches.	Length—feet and inches.	Flues.			Dome.		Thickness of Shell—inches.	Thickness of Head—inches.	Length of Furnace—feet.	Stack.		Weight of Boiler—pounds—about.	Weight of Boiler and Fixtures—pounds—Complete.
				Number.	Diameter—inches.	Length—feet.	Diameter—inches.	Height—inches.				Diameter—inches.	Height—feet.		
1	15	36	8′ 11″	30	3	8	20	20	1/4	3/8	3	18	26	2,950	5,350
2	20	36	10′ 11″	30	3	10	20	20	1/4	3/8	3½	18	30	3,500	5,900
3	25	42	11′	38	3	10	24	24	9/32	3/8	3½	20	30	4,400	7,100
4	30	42	13′	38	3	12	24	24	9/32	3/8	4	20	36	5,000	7,800
5	35	44	13′	46	3	12	24	26	5/16	3/8	4	22	36	5,500	8,700
6	40	48	13′ 2″	52	3	12	24	28	5/16	3/8	4	24	36	6,400	9,900
7	45	50	14′ 2″	52	3	13	30	30	5/16	3/8	4	24	36	6,800	10,400
8	50	54	13′ 2″	58	3	12	30	30	5/16	3/8	4	26	36	7,600	11,500
9	60	54	16′ 2″	58	3	15	30	30	11/32	3/8	4½	26	45	8,550	12,750
10	70	60	15′ 4″	76	3	14	30	30	11/32	7/16	4½	28	45	10,000	14,500
11	75	60	16′ 4″	76	3	15	30	30	11/32	7/16	4½	28	50	10,500	15,100
12	80	60	17′ 4″	76	3	16	30	36	11/32	7/16	5	28	55	11,200	16,100
13	90	66	16′ 5″	100	3	15	36	36	3/8	7/16	5	32	55	13,500	19,100
14	100	66	17′ 5″	100	3	16	36	36	3/8	7/16	5	32	55	14,200	19,800
15	125	72	17′ 6″	132	3	16	36	36	7/16	1/2	5	36	60	17,200	24,000

The upright tubular boiler is given less heating-surface than the above, is much lighter, and is less economical. The locomotive type of stationary boiler has about the same weight as the above, but rather less heating-surface.

According to Professor Rankine,* a very useful mode of comparing the capacities of different boilers is to divide the boiler-space by the area of heating-surface, and thus is obtained a mean depth. Of the following examples, the first three are given on the authority of Mr. Fairbairn's "Useful Information for Engineers:"

	"Mean depth." Feet.
Plain cylindrical egg-ended boiler, with external flues below and at each side, but no internal flues	3.50
Cylindrical boiler with external flues, and one cylindrical internal flue	1.65
Cylindrical boiler with external flues, and two cylindrical internal flue	1.00
Stationary boilers according to Mr. Robert Armstrong's rules	3.00
Multitubular marine boilers, about	0.50
Locomotive boilers, and boilers composed of water-tubes, average about	0.10

Boilers of large size and capacity exhibit steadiness in the pressure of the steam, ready deposition of impurities, space for the collection of sediment, and freedom from priming. Those of small capacity excel in rapid raising of the steam to any required pressure, small surface for waste of heat, economy of space and weight, of special importance on board ship, greater strength with a given quantity of material, and smaller damage in the event of an explosion.

Mr. D. K. Clark considers that we may, in ordinary locomotive practice, take the economical consumption of fuel as proportional to the square of the area of heating-surface, and make the grate-area vary in the same proportion. He adopts nine to one as the standard and desirable evaporation of water as compared with weight of fuel, makes the maximum and minimum allowable rates of combustion 150 and 14 pounds per square foot of grate, and the maximum evaporation in locomotive boilers about 22 cubic feet per hour.† A rate of combustion of 112 pounds is considered a practical maximum, the ratio of heating to grate surface being 85 to 1.

* Steam-engine and Prime Movers.

† Railway Machinery, p. 165.

162. The Usual Rates of Evaporation and the effect of varying the proportions of tubes has been well determined by the experiments of Isherwood and others.

The proportions of flues and tubes vary somewhat in practice; but it will be found seldom advisable to make tubes more than 50 or 60 diameters in length. Where the heating-surface consists principally of tubes, the efficiency will be found to vary with their length nearly as follows:

Length of tube (diameters)......	60	50	40	30	20
Water per unit weight of fuel......	12	11	10	9	8

When the ratio of heating to grate area was 25 to 1, Isherwood found the evaporation to vary thus:

Fuel per hour......	8	10	12	16	20	24
Evaporation......	10 5	10.1	9.5	8.2	7.3	6.8

which series is represented by

$$W=\frac{21}{\sqrt[8]{F}}, \text{ nearly.}$$

Clark obtained with locomotives an equal evaporation with

Fuel (coke)......	15	25	38	56	76	98	125	153
Ratio of H. S. to G. S......	30	40	50	60	70	80	90	100

the evaporation being constant at 9 of water to 1 of fuel, which may be expressed by

$$S = 8\sqrt{F}, \text{ nearly,}$$

S being the ratio of the two areas and F the weight of coke burned on the unit of area of grate.

In estimating area of heating-surfaces the whole surface exposed to the hot-furnace gases is reckoned. The formula for efficiency already given illustrates the progressive variation of the evaporative power with change of proportions of boiler.

163. The Relation of Size of Boiler to Quality of Steam demanded is one that occasionally becomes worthy of consideration. Where the steam is required for driving steam-engines it is very important that it should be thoroughly dry, and it is an advantage to moderately superheat it. Maximum economy cannot be attained where wet steam is used. A boiler

attached to a steam-engine, and especially where fuel is costly and efficiency important, should have ample heating-surface, some superheating-surface if practicable, ample extent of water-surface area to permit free separation of steam and water, and large steam-space.

Steam employed for heating purposes is not necessarily dry; it may carry a large amount of water with it into the system of heating-coils or radiators, and yet give good results, if the latter are of large section. Where the pipes are of restricted area of section, however, wet steam flowing less freely than when dry or superheated, there may result such a retardation of flow and of circulation as may cause considerable increase of cost. This has been found sufficiently great, in some, cases, to justify drying, and perhaps superheating, the exhaust-steam from engines where used for heating purposes. As a general rule, the boiler must be made a trifle larger to supply perfectly dry steam and do good work.

In the use of steam for heating purposes, one square foot of boiler-surface will supply from 7 to 10 square feet of radiating surface. Small boilers should be larger proportionately than large boilers. Each horse-power of boiler will supply from 250 to 350 feet of 1-in. steam-pipe, or 80 to 120 square feet of radiating surface.

Under ordinary conditions one horse-power will heat about—

Brick dwellings, in blocks, as in cities.......	15,000 to 20,000	cub. ft.
" stores " "	10,000 " 15,000	" "
" dwellings, exposed all around.........	10,000 " 15,000	" "
" mills, shops, factories, etc............	7,000 " 10,000	" "
Wooden dwellings, exposed..................	7,000 " 10,000	" "
Foundries and wooden shops	6,000 " 10,000	" "
Exhibition buildings, largely glass, etc.......	4,000 " 10,000	" "

The system of heating mills and manufactories by means of pipes placed overhead is recommended.

The air required for ventilation is usually warmed by the "indirect" system of radiation, the current passing through boxes or chambers in which a sufficient amount of pipe is coiled to heat it well. From 5 to 15 cubic feet per individual per

minute are allowed, the former in crowded halls, the latter in dwellings, and about one tenth as much for each gas-burner or lamp.

164. **The Number and Size of Boilers** to be used in any case in which considerable power is demanded is determined mainly by practical considerations related to their construction. As a rule, the larger boiler is more economical in first cost and in operation, within certain limits, than several smaller boilers of equal aggregate power. But passing a limit which cannot be usually very exactly defined, expense is increased, transportation becomes difficult, location and setting involve problems difficult of solution, and management becomes less easy. Mr. Leavitt has, however, constructed stationary boilers, of a peculiar modification of the locomotive type, of as high as one thousand horse-power; and marine boilers of equal or greater power have been built not infrequently for steamers plying on the larger rivers of the United States. Stationary boilers of 100 horse-power and marine boilers of 500 are more usual and more commonly suitable sizes. Locomotive boilers are necessarily always sufficiently large to supply all the power demanded of the engine.

The type of boiler has much influence on the limit of size. Plain "cylinder boilers" are rarely made more than from 3 to 4 feet (0.9 to 1.2 m.) in diameter, and this restricts the grate-area so that the power derivable from a single such boiler is seldom more than 15 or 20 horse-power, and is usually much less. The more complex structures often include several furnaces, and yield from 100 to 200 horse-power each on land, and more at sea.

Makers in the United States usually allow 15 square feet of heating-surface and one of grate to the horse-power, in plain cylindrical boilers, and the same area of heating-surface, but a fourth and a half less grate-area, respectively, with flue-boilers and tubular boilers, where estimating for the market.

M. de Pambour found the priming of French locomotive boilers in 1834 to amount to about 30 per cent; M. de Chatellier, in 1843–4, found it to be 30 to 50 per cent; but a large proportion of the moisture measured was undoubtedly the

product of cylinder condensation, for which loss Clarke allowed as follows: *

Ratio of Expansion.	Condensation.	
	Per cent. of Steam indicated.	Per cent. of Total Steam.
1.25	12	11
1.67	12	11
2 00	12	11
2.50	21	17
3.67	32	24
5.00	46	32
8.33	73	42

—which figures indicate the proportion of steam by weight to be added to that calculated for the ideal engine, to obtain the probable requirement of the real engine.

Builders of the more economical classes of engines supply them with boilers often of less size than the accepted standard rating would dictate, as they demand less steam per horse-power than the average engine. A good engine of moderate size, with an automatically governing and adjusting valve-gear, if condensing, should give good results on as low as seven or eight square feet of heating-surface per actual horse-power, and if non-condensing, with ten or twelve square feet. Large engines are given a smaller allowance of heating-surface, proportionally, than are small engines.

165. **The Standard Sizes of Tubes** have become well settled by custom. So large an element of boiler-construction necessarily assumes, with time, a somewhat rigid set of proportions. The sizes employed range from 1 or 1¼ inch (25.4 to 31 mm.) diameter in the smallest boilers, to 2 or 2½ inches (51 to 63.5 mm.) in the locomotive and other boilers of moderate size; and to 3 or 4 inches (76 or 102 mm.), or even 5 or 6 inches (1.27 or 1.52 mm.), in large boilers, or where a very free draught or greater convenience of access are required. Water-tube boilers

* Railway Machinery, p. 144.

are commonly given tubes 4 or 5 inches (102 or 127 m.) in diameter. The length of the tube is customarily not above 50 or 60 diameters in stationary boilers, and two thirds this length in marine work. The spaces between the tubes should be about one half their diameter; they are, however, usually placed much closer. All tubes in our market are gauged to British measures, as below:

When the dimensions of a tubular boiler are given, the outside diameter of the tubes is usually stated, so that twice the thickness must be subtracted to obtain the diameter to be used in the calculation of heating-surface. The thickness of tubes by different makers varies somewhat, but those given below are average values, and can be used without serious error. The table gives dimensions of standard sizes of tubes.

STANDARD TUBES.

Outside diameter in inches.	Thickness in inches.	Internal diameter in inches.	Internal diameter in feet.	Heating-surface in square feet, per foot of length.
1.25	0.072	1.106	0.0922	0.3273
1.5	0.083	1.334	0.1112	0.3926
1.75	0.095	1.560	0.1300	0.4589
2.	0.095	1.810	0.1508	0.5236
2.25	0.095	2.060	0.1717	0.5890
2.5	0.109	2.282	0.1902	0.6545
2.75	0.109	2.532	0.2110	0.7200
3.	0.109	2.782	0.2318	0.7853
3.25	0.120	3.010	0.2508	0.8508
3.5	0.120	3.260	0.2717	0.9163
3.75	0.120	3.510	0.2925	0.9817
4.	0.134	3.732	0.3110	1.0472
4.5	0.134	4.232	0.3527	1.1790
5.	0.148	4.704	0.3920	1.3680
6.	0.165	5.770	0.4808	1.5708
7.	0.165	6.770	0.5642	1.8326
8.	0.165	7.770	0.6475	2.0944
9.	0.180	8.640	0.7200	2.3562
10.	0.203	9.594	0.7995	2.5347

The following are the dimensions of standard tubes as made by some of the best makers in the United States:

LAP-WELDED CHARCOAL-IRON BOILER-TUBES.

Standard Dimensions.

Diameter—external.	Diameter—internal.	Thickness.	Wire Gauge.	Circumference—external.	Circumference—internal.	Transverse areas—external.	Transverse areas—internal.	Transverse areas—metal.	Length per sq. ft. of surface—external.	Length per sq. ft. of surface—internal.	Weight per foot.
In.	In.	In.	No.	In.	In.	Sq. in.	Sq. in.	Sq. in.	Feet.	Feet.	Lbs.
1.	.86	.072	15	3.14	2.69	.78	.57	.21	3.82	4.46	.71
1.125	.98	.072	15	3.53	3.08	.99	.76	.24	3.39	3.89	.8
1.25	1.11	.072	15	3.93	3.47	1.23	.96	.27	3.06	3.45	.89
1.32	1.15	.083	14	4.12	3.6	1.35	1.03	.32	2.91	3.33	1.08
1.375	1.21	.083	14	4.32	3.8	1.48	1.15	.34	2.78	3.16	1.13
1.5	1.33	.083	14	4.71	4.19	1.77	1.4	.37	2.55	2.86	1.24
1.625	1.43	.095	13	5.1	4.51	2.07	1.62	.46	2.35	2.66	1.53
1.75	1.56	.095	13	5.5	4.9	2.4	1.91	.49	2.18	2.45	1.66
1.875	1.68	.095	13	5.89	5.29	2.76	2.23	.53	2.04	2.27	1.78
2.	1.81	.095	13	6.28	5.69	3.14	2.57	.57	1.91	2.11	1.91
2.125	1.93	.095	13	6.68	6.08	3.55	2.94	.61	1.8	1.97	2.04
2.25	2.06	.095	13	7.07	6.47	3.98	3.33	.64	1.7	1.85	2.16
2.375	2.16	.109	12	7.46	6.78	4.43	3.65	.78	1.61	1.77	2.61
2.5	2.28	.109	12	7.85	7.17	4.91	4.09	.82	1.53	1.67	2.75
2.75	2.53	.109	12	8.64	7.95	5.94	5.03	.9	1.39	1.51	3.04
2.875	2.66	.109	12	9.03	8.35	6.49	5.54	.95	1.33	1.44	3.18
3.	2.78	.109	12	9.42	8.74	7.07	6.08	.99	1.27	1.37	3.33
3.25	3.01	.12	11	10.21	9.46	8.3	7.12	1.18	1.17	1.26	3.96
3.5	3.26	.12	11	11.	10.24	9.62	8.35	1.27	1.09	1.17	4.28
3.75	3.51	.12	11	11.78	11.03	11.04	9.68	1.37	1.02	1.09	4.6
4.	3.73	.134	10	12.57	11.72	12.57	10.94	1.63	.95	1.02	5.47
4.25	3.98	.134	10	13.35	12.51	14.19	12.45	1.73	.9	.96	5.82
4.5	4.28	.134	10	14.14	13.20	15.9	14.07	1.84	.85	.9	6.17
4.75	4.48	.134	10	14.92	14.08	17.72	15.78	1.94	.8	.85	6.53
5.	4.7	.148	9	15.71	14.78	19.63	17.38	2.26	.76	.81	7.58
5.25	4.95	.148	9	16.49	15.56	21.65	19.27	2.37	.73	.77	7.97
5.5	5.2	.148	9	17.28	16.35	23.76	21.27	2.49	.7	.73	8.36
6.	5.67	.165	8	18.85	17.81	28.27	25.25	3.02	.64	.67	10.16
7.	6.67	.165	8	21.99	20.95	38.48	34.94	3.54	.55	.57	11.9
8.	7.67	.165	8	25.13	24.1	50.27	46.2	4.06	.48	.50	13.65
9.	8.64	.18	7	28.27	27.14	63.62	58.63	4.99	.42	.44	16.76
10.	9.59	.203	6	31.42	30.14	78.54	72.29	6.25	.38	.4	20.99
11.	10.56	.22	5	34.56	33.17	95.03	87.58	7.45	.35	.36	25.03
12.	11.54	.229	4.5	37.7	36.26	113.1	104.63	8.47	.32	.33	28.46
13.	12.52	.238	4	40.84	39.34	132.73	123.19	9.54	.29	.3	32.06
14.	13.5	.248	3.5	43.98	42.42	153.94	143.22	10.71	.27	.28	36.
15.	14.48	.259	3	47.12	45.5	176.71	164.72	11.99	.25	.26	40.3
16.	15.43	.284	2	50.26	48.48	201.06	187.04	14.02	24	.25	47.11
17.	16.4	.3	1	53.41	51.52	226.98	211.24	15.74	.22	.23	52.89
18.	17.32	.34	0	56.55	54.41	254.47	235.61	18.86	.21	.22	63.32

The following table* gives the draught-areas of boiler-tubes and flues, which have been computed on the basis of the thickness of such tubes taken from the price-lists of American manufacturers:

* *American Engineer*, 1885.

DRAUGHT-AREAS OF TUBES AND FLUES.

External diameter in inches.	Draught-area in square inches.	Draught-area in square feet.	Number of tubes or flues = 1 square foot of draught-area.
1	.575	.0040	250.0
1¼	.968	.0067	149.3
1½	1.389	.00964	103.7
1¾	1.911	.0133	75.2
2	2.575	.0179	55.9
2¼	3.333	.0231	43.3
2½	4.083	.0284	35.2
2¾	5.027	.0349	28.7
3	6.070	.0422	23.7
3¼	7.116	.0494	20.2
3½	8.347	.0580	17.2
3¾	9.676	.0672	14.9
4	10.93	.0759	13.2
4½	14.05	.0976	10.2
5	17.35	.1205	8.3
6	25.25	.1753	5.7
7	34.94	.2426	4.1
8	46.20	.3208	3.1
9	58.63	.4072	2.5
10	72.23	.5016	2.0

In a flue-return tubular boiler the area of flues should be about 20 per cent, and the draught-area of uptake about 25 per cent greater than the draught-area of tubes. Good conditions for combustion and steaming are realized when the grate-surface is 8 times and the heating-surface about 200 to 240 times the draught-area of tubes.

The location and arrangement of fire-tubes has an important bearing on the distance by which they may be safely separated. In locomotive boilers, where they only check the rise of currents laden with steam produced by their own action, they may be set closer than in those boilers, as many marine boilers, in which they lie above a crown-sheet from which enormous quantities of steam are liberated, which steam, as well as that made by the tubes themselves, must traverse the intermediate spaces. Where the circulation is forced and rapid the tubes may also be crowded more than where natural and sluggish. In locomotive boilers, the tubes, which are ordinarily from 1¾ to 2 inches in diameter, are set apart from

one third to one fifth their diameters; but the larger space is probably none too great.

166. **The Details of the Problem**, as coming to the designer and the constructor of the steam-boiler, are so largely matters determined by experience, rather than by any scientific system or calculation, that much thought must be given to their consideration from the point of view of the practitioner in engineering and of the artisan engaged in building such structures—from the boiler-maker's side rather than from that of the man of science.

The selection of the iron or steel for shell, for stays, or of the rivets; the choice of style of riveting; the determination of the character of seam and lap; the decision of the question whether the use of reinforced seams or of heavier plates is likely to prove best in the end; the choice of type of boiler even, in view of known peculiarities of location or other conditions: these must all be settled in conference with the boiler-maker, even if not directed absolutely by him. It seldom happens that the engineer making the designs feels competent to act throughout without consultation with his lieutenants in the workshop.

The method of designing in its details, as practised in the case of familiar forms of boiler, will be given in the next chapter.

CHAPTER VIII.

DESIGNING STEAM-BOILERS—PROBLEMS IN DESIGN.

167. **The General Considerations** determining the design of a steam-boiler are, mainly, the following:

(1) It must supply a defined quantity of steam in a specified unit of time, or it must have a certain power.

(2) It must be as absolutely safe as it is practicable to make it.

(3) It must have reasonably high efficiency, and must be capable of working at the lowest total expense for fuel, attendance, interest on first cost, taxes, insurance, and all other running expenses, in proportion to work done, that may be attainable.

(4) It must be well suited to the location, and to all the special conditions affecting it when in operation.

Marine steam-boilers must, for example, be given the minimum practicable weight and volume, since it costs as much to carry a ton of boiler as a ton of cargo, and every cubic foot occupied by boilers, fuel, or machinery displaces a cubic foot of paying load. Naval boilers, also, must usually be kept as low in the ship as possible to reduce risk of injury by shot. So important are these elements in naval construction, that the practical limits of space and power on shipboard are commonly fixed by the space occupied by boilers; and the reduction of grate-area is the first problem attacked by the naval architect and engineer seeking high speed, whether for yachts, torpedo-boats, or larger craft.

168. **The Parts and Details** of the steam-boiler may be defined as follows:*

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* See Rankine, Steam-engine, p. 449.

The usual arrangements of furnace and boiler may be divided into three principal classes:

(I.) In the external furnace, or "outside-fired boiler," the furnace is wholly outside of the boiler; so that the boiler forms *part* of the superficies of the furnace; the other sides of the furnace being usually of fire-brick. Examples of this are the wagon boiler, the plain cylindrical boiler without internal flues, and all boilers in which the water and steam are contained in tubes surrounded by the flame.

(II.) In the internal-furnace or "inside-fired boiler" the fire-chamber is enclosed within the boiler, as in boilers with furnaces contained in horizontal cylindrical internal flues, in most marine boilers, and in all locomotive boilers.

(III.) The detached furnace, which is a fire-chamber built of fire-brick, in which the combustion is completed before the gas comes in contact with the boiler.

The principal parts and appendages of a furnace are—

(1) The *furnace proper*, or *firebox*, being the chamber in which the solid constituents of the fuel, and the whole or a part of its gaseous constituents, are consumed.

(2) The *grate*, which is composed of alternate bars and spaces, to support the fuel and to admit air.

(3) The *hearth* is a floor of fire-brick, on which, instead of on a grate, the fuel is burned in some furnaces.

(4) The *dead-plate* or *dumb-plate*, that part of the bottom of the furnace which consists of an iron plate simply.

(5) The *mouth-piece*, through which fuel is introduced, and often some air. The lower side of the mouth-piece is the dead-plate. In many furnaces there is no mouth-piece.

(6) The *fire-door* closes the doorway, and may or may not have openings and valves in it to admit air. Sometimes the duty of a fire-door is performed by a heap of fuel closing up the mouth of the furnace.

(7) The *furnace-front* is above and on either side of the fire-door.

(8) The *ash-pit* is the space into which the ashes fall, and through which, in most cases, the supply of air enters.

(9) The *ash-pit door* is used to regulate the admission of air.

(10) The *bridge* is a low wall at the end of the furnace over which the flame passes to the chimney. This is meant when "the bridge" is spoken of ordinarily; but the word *bridge*, or bridge-wall, is also applied to any partition having a passage for flame or hot gas over it. Bridges are of fire-brick, or of plate iron and hollow, so as to form part of the water-space of the boiler, and are then called *water-bridges*. The top of a water-bridge should slope upwards at the ends to allow of the rapid escape of the steam on its internal surface. A water-bridge may project downwards from the boiler above the furnace; it is then called a *hanging bridge*.

(11) The *combustion* or *flame-chamber* is the space behind the bridge in which the combustion of the furnace-gases is completed. It may be lined with brick or tile to prevent extinction of the flame.

(12) *Bafflers* or *diffusers* are partitions so placed as to promote the circulation of the gas over the heating surface of the boiler or of the currents of water within. Bridges fall under this head.

(13) *Dampers* are valves placed in the chimney, flues, or passages to regulate the draught.

The principal parts and appendages of a boiler are:

(1) The *shell* of the boiler. The figures usually employed for the shells of boilers are the cylindrical and the plane, and combinations of those two figures. In locomotive boilers, part of the shell is a rectangular box, containing within it the firebox. The shells of marine boilers are often of irregular shapes, adapted to the space in the ship which they are to occupy, and approximating more or less to rectangular forms. For heavy pressures, however, they are usually cylindrical, with plane ends.

(2) The *steam-chest*, *steam-drum*, or *dome* is a part which rises above the rest of the boiler, and provides a space in which the steam may deposit any spray carried by it; it is usually cylindrical.

(3) The *furnace* or *firebox* is usually within the boiler, so placed as to be covered with water. In cylindrical boilers it is often in one end of a horizontal cylindrical flue, as in Cornish

boilers; in locomotive boilers it is a rectangular box. In marine boilers it is usually rectangular in the older kinds of boiler, and cylindrical in the high-pressure cylindrical tubular boiler.

(4) A *tube-plate* forms part of the shell of the boiler, or one side of an internal firebox, or flue, and is perforated with holes, into which the ends of the tubes are fixed. Each set requires a pair, one for each end of the tubes.

(5) The *man-hole* is an opening in the top or end of the boiler, large enough to admit a man. The bolts holding the man-hole cover must be capable of safely bearing their load. Commonly the cover opens inwards, and is kept closed by the pressure of the steam, and is held by bolts and nuts to a cross-bar outside the man-hole.

(6) *Hand-holes* are openings usually placed at or near the lowest part of a boiler, and large enough to admit the hand, which are opened occasionally for the discharge of sediment.

(7) The *blow-off apparatus* consists of a cock at the bottom of the boiler, which is opened to cleanse the boiler by emptying it or to discharge brine, and prevent salt from collecting. The surface blow-cock discharges the *scum* which collects on the surface of the water.

(8) The *pressure-gauge* shows the pressure within the boiler.

(9) The *water-gauge* shows the level of the water in the boiler. Gauge-cocks are set at different levels: one at the proper water-level, another a few inches above, and a third a few inches below. Opening these the engineer ascertains the level of the water. The *glass water-gauge* consists of a strong glass tube, communicating with the boiler above and below the water-level. The level of the water is thus rendered visible. Every boiler ought to be provided with *both* forms of gauge.

(10) *Clothing* and lagging prevent waste of heat. The former is made sometimes of hair felt, the latter covers it with a layer of thin wooden boards. Asbestus, ashes, and other materials are similarly used. Hair-felt has sometimes been found to singularly accelerate internal corrosion.

169. The Design of the Plain Cylindrical Boiler is the simplest problem of its class. This boiler, consisting of only a cylindrical shell and plane or domed heads, is not likely to afford opportunity for the display of either great knowledge in design and construction or of ingenuity in its details. This type is selected when cheap fuel or bad water make it unwise to adopt more economical forms.

The shell is usually about twelve diameters in length, but is sometimes made fifteen or even twenty, and double the last figure has been known. In some cases this boiler has been built as a cylindrical ring—an annulus of large diameter and of circular section. Common sizes for this class of boiler range from 24 to 36 inches (63 to 91 cm.) diameter of shell, and 24 to 36 feet (7.3 to 11 m.) long. As the diameter of the boiler usually fixes the width of grate, and as the length of grate is rarely found to be profitably extended beyond about 6 feet (1.8 m.), the power of the boiler has a very simple relation to its size. The ratio of heating to grate surface is always thus made small, and the boiler is necessarily uneconomical of fuel.

This boiler is usually designed with single-riveted seams throughout, although safety and even ultimate economy of cost and operation during its lifetime may be sometimes gained by double-riveting the longitudinal seams; which would thus be strengthened in the proportion of about 70 to 55 or 60, or not far from 20 per cent, and the whole structure would be made correspondingly safer.

The thickness of shell is determined by the pressure of steam to be carried and the factor of safety adopted. Assuming the iron to have a tenacity of 50,000 pounds per square inch (3515 kilogs. per sq. cm.), the joints will have, as may be assumed, 0.60 this resisting power, and the boiler-shell is to be calculated with this loss in mind, and will be made as if the sheets had a tenacity of 30,000 pounds per square inch (2109 kgs. per sq. in.), and were of uniform strength through the seams. In illustration, assume it to be demanded that a "36-inch cylindrical boiler" shall be designed to sustain a pressure of 100 pounds per square inch (7 kilogs. per sq. cm.). The thickness of shell should be.

$$t = \frac{fpd}{2kT} = \frac{6 \times 100 \times 36}{2 \times 0.55 \times 50{,}000} = \tfrac{3}{8},$$

when p, d, and T are the pressure and the diameter of the shell and the tenacity of the metal, and k is the "efficiency" of the seam, which we may here assume to have $k = 0.55$, or 55 per cent of the strength of the solid sheet; the factor of safety is taken as $f = 6$. The thickness of shell should be three-eighths of an inch (1 cm. nearly). Such thickness is not usual, and a factor of safety of four and a thickness of one quarter of an inch (0.635 cm.) is more common for this case in general practice, and is allowed by the law as may be seen in article 55, to which reference may be made for tabulated legal dimensions of this class of boilers.

The heads of the cylindrical boiler are sometimes made of cast-iron, the thickness made empirically from $1\frac{1}{2}$ to $2\frac{1}{2}$ inches (3.8 to 6.4 cm.) for diameters of from 24 to 36 inches (63 to 91 cm.) respectively; they are often of sheet-iron of the same thickness as the shell, and domed to give them resisting power, —an excellent construction, especially when pressed into exact shape in the forming die of the hydraulic press. When the heads are plane, they are stayed either by stays running to the sides of the boiler at angles of from 10° to 30°, or by triangular "gusset-plates" riveted to the heads and sides. This last construction is subject to the objection that the gusset-plates are necessarily irregularly strained and liable to tear. Stay-rods are of sufficient size to safely carry the whole pressure received on the heads, and securing both heads, pass from the one to the other, the whole length of the boiler, with adjustable nuts at each end, outside the head, and inside as well.

A dished head is probably the best form to give, whether of boiler, of dome, or of steam and mud drums. As shown by Mr. Robert Briggs,* equal strength with the shell or with a stayed head can be obtained by giving the proper form to the head-sheet without any staying. Thus it is known that the strength of a spherical shell is twice as great as that of the

* Journal Franklin Institute, 1878.

cylinder of the same diameter, when both shell and cylinder have the same thickness; or that a spherical shell possesses the same strength as a cylindrical shell of the same thickness, when the radius of the spherical surface is equal to the diameter of the cylinder. When the rule stated is applied to the head of the dome or of the boiler, which is formed to a part of a spherical surface whose radius is the diameter of the dome or boiler, the head is "dished" out 0.134 the diameter of the head, in order to give the same strength to resist internal pressure, for both head and shell, of the same thickness of iron. A small allowance is needed for the thinning of the sheet-iron, in *dishing*. This allowance is easily computed thus: The surface of the flat circular plate is to that of the dished plate as 1 to 1.072, and the thickness of the circle, before dishing, should be about 7 per cent (one fourteenth) greater than that of the shell. The flangeing of the head will inevitably upset the flange itself to a thickness much above the original; and a dished head of ordinary thickness will be much stronger than the shell sheets at the joints, where they are weakened by rivet-holes, even if put together with the double-riveted longitudinal seams.

Heads of sheet-iron are usually made ten or, better, twenty per cent heavier than the shell.

A man-hole is commonly located in the most accessible end of the boiler, and, often, a hand-hole through which the boiler may be completely drained, and all mud and scale removed. The feed-pipe usually enters through the front head, but sometimes at the rear. It should always be at a part readily reached for inspection and repairs. If on the shell, the opening should always be reinforced by a heavy wrought-iron ring and the strength of the boiler thus increased rather than diminished by its introduction. The ring should be riveted inside the opening. The steam-pipe is sometimes led directly out of the top of the boiler, but is better placed in connection with a steam-dome or steam-drum, in order to obtain as dry steam as is possible. The safety-valve should here, as in all other cases, be so placed that no accident or carelessness can close its communication with the steam-space; a stop-valve placed between it

and the boiler has been known to produce a disastrous explosion, when shut by an ignorant or thoughtless attendant.

Gauge-cocks should always be attached even if the glass water-gauge is in use. The experienced manager of boilers never feels perfect confidence in any other water-level indicator, however convenient and generally accurate. In setting the gauge-cocks it is usual to allow about one third the volume of the boiler for steam-space. The following table, calculated by Mr. W. F. Worthington, gives the volume of this space in unity of length of the shell, British measures:

TABLE FOR CALCULATING THE CAPACITY OF THE STEAM-SPACE IN CYLINDRICAL BOILERS.

DIAM	30"	32"	34"	36"	38"	40"	42"	48"	54"	60"	66"	72"	
In. Distance from water-line to top of boiler.	Multipliers (cubic feet).												In. Distance from water-line to top of boiler.
1	.05	.05	.05	.05	.05	.06	.06	.06	.06	.07	.07	.08	1
2	.14	.14	.15	.15	.16	.16	.16	.17	.19	.20	.21	.21	2
3	.25	.26	.27	.28	.29	.30	.30	.32	.34	.37	.38	.39	3
4	.39	.40	.42	.43	.44	.45	.46	.50	.53	.55	.58	.61	4
5	.53	.56	.57	.59	.61	.63	.64	.69	.73	.78	.82	.85	5
6	.70	.72	.75	.77	.80	.82	.83	.91	.96	1.02	1.08	1.12	6
7	.87	.90	.93	.96	.99	1.02	1.05	1.14	1.20	1.27	1.35	1.41	7
8	1.05	1.09	1.13	1.17	1.20	1.24	1.27	1.37	1.47	1.55	1.63	1.71	8
9	1.24	1.29	1.33	1.38	1.42	1.47	1.51	1.62	1.73	1.85	1.94	2.04	9
10	1.43	1.49	1.55	1.59	1.65	1.70	1.75	1.89	2.02	2.14	2.26	2.38	10
11	1.63	1.69	1.76	1.82	1.89	1.95	2.00	2.18	2.33	2.46	2.59	2.74	11
12	1.83	1.91	1.98	2.06	2.13	2.20	2.26	2.46	2.63	2.79	2.95	3.08	12
13	2.04	2.13	2.21	2.30	2.38	2.46	2.53	2.75	2.93	3.12	3.31	3.46	13
14	2.24	2.35	2.44	2.53	2.63	2.72	2.80	3.04	3.25	3.47	3.67	3.85	14
15		2.57	2.68	2.79	2.89	2.98	3.08	3.35	3.61	3.84	4.05	4.26	15
16			2.92	3.03	3.15	3.26	3.37	3.66	3.94	4.19	4.43	4.67	16
17				3.28	3.41	3.53	3.65	3.98	4.29	4.57	4.83	5.09	17
18					3.67	3.81	3.93	4.30	4.63	4.95	5.23	5.53	18
19						4.08	4.22	4.63	5.00	5.32	5.66	5.97	19
20							4.52	4.96	5.35	5.72	6.08	6.41	20
21								5.28	5.72	6.12	6.50	6.84	21
								5.61	6.10	6.51	6.92	7.30	22
								5.95	6.46	6.92	7.35	7.76	23
									6.82	7.33	7.79	8.24	24
									7.20	7.75	8.22	8.71	25
									7.57	8.15	8.70	9.20	26
										8.57	9.14	9.68	27
										8.97	9.59	10.17	28
										9.39	10.04	10.67	29
											10.49	11.16	30
											10.94	11.62	31
											11.39	12.12	32
												12.62	33
												13.12	34
												13.63	35

RULE.—Multiply the number in the table by the length of the boiler in feet, and the product will be the capacity of the steam-space in cnbic-feet.

In designing this, as any other boiler having a cylindrical shell and fired externally, it is advisable to secure as large

sheets, and as few seams on the under side and where exposed to the action of the fire and the furnace gases, as possible. Boilers are now often made with but a single sheet extending from end to end, and of such width that all longitudinal seams are above the reach of flame.

The steam-space should be of such volume that the variation of pressure produced by each stroke of the engine should be unimportant. An old rule given by Bourne made the space not less than twelve times the volume of steam taken out by the engine at each stroke; it may, however, be less for a given power as the speed of rotation of the engine is higher and as the ratio of expansion is increased. Tredgold would restrict the variation of steam-pressure at each stroke to about three per cent of the normal amount, which would, if V be the volume of steam-space of the boiler, S that of the single cylinder, up to the point of "cut-off," and r the ratio of expansion, adopting Tredgold's coefficient, 0.033,

$$V = 30 \frac{r - 1}{r} S.$$

For coupled engines, a much smaller space may be allowed.

According to Shock,* marine boilers of the older types work dry when they contain in their steam-space a supply sufficient for the engine during 14 seconds and give wet steam if the steam-space is sufficient for but 12 seconds; while the more modern forms of high-pressure boilers will only furnish dry steam when containing a volume equal to 20 seconds' supply. Steam-space of considerable altitude is most effective.

170. **Stationary Flue-boilers** are designed, as to dimensions of shell, very much as are plain cylindrical boilers. They are commonly of somewhat larger diameter and of comparatively less length.

The Cornish boiler, in which the single great flue serves also as furnace, is rarely made of less than 6 feet (1.8 m.) in diameter, as a smaller flue than that so obtained gives too contracted

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* Steam-boilers, p. 306.

a furnace. The length of this boiler is usually from 25 to 40 feet (7.6 to 12 m.). The thickness of shell is made about ½ inch (1.27 cm.) and of flue ⅜ inch (0.95 cm.) for the shorter and ½ inch (1.27 cm.) for the greater length, the steam-pressure adopted being usually about 40 pounds per square inch (3 at.). Both should, however, be carefully computed by the methods already given (§§ 55, 56), and a good factor of safety—not less than 6—is advised to be adopted and permanently maintained. The flue is nearly always one half the diameter of the shell. Where the boiler is long, and the flue thus becomes structurally weak, strengthening rings, or flanged girth-seams, should be adopted to insure greater strength and safety in the flue, which should, because of its special liability to injury and general, as distinguished from local, failure, be even safer against collapse than the shell against bursting. Collapse of the flue, however, is less likely to be disastrous to life and surrounding property than explosion of the shell. The heads are so well stayed by the flue that they require no other bracing below the water-line; above that level, however, they should be stayed by either stay-rods or gusset-pieces, like the plain cylindrical boiler. The same remarks also here apply, relative to appurtenances of the boiler, as in the preceding case.

Multiflue Boilers are constructed either with or without fireboxes. The latter will be considered more at length in later articles. Flue-boilers without fireboxes are simply composed of a cylindrical shell with plane heads, and having flues running from end to end, below the water-line, and secured in the heads, at each end, by means of flanges turned in those "flue-sheets" and riveted to the ends of the flues. These flanges are usually turned inwards, but are sometimes on the exterior, the projecting end of the flue, extending beyond the plane of the head. The number and size of these flues is determined mainly by the judgment of the designer, and no rule exists; but the better the water used and the more valuable the fuel consumed, the more numerous the flues. Where two are put in, they are commonly about one third the diameter of the boiler, each, and are set side by side below the horizontal diametral line of the shell. When more are used, the number

is first increased to five, each of about one fourth the size of the boiler-shell. With still further subdivision the designer puts them in as he best can, ordinarily keeping their centres at the intersections of horizontal and vertical lines, set apart distances equal to the diameter of flue plus the desired space for circulation, which varies from one half to one fourth the diameter of the flue accordingly as the latter are more or less numerous. Ample room for circulating currents is no less essential to efficiency than extent of heating-surface, and, as a matter of safety, more so. Small flues are commonly made of iron of the same, or somewhat less, thickness with the shell, and, when numerous, have an excess of strength over that indicated by calculation and a correspondingly increased margin for safety.

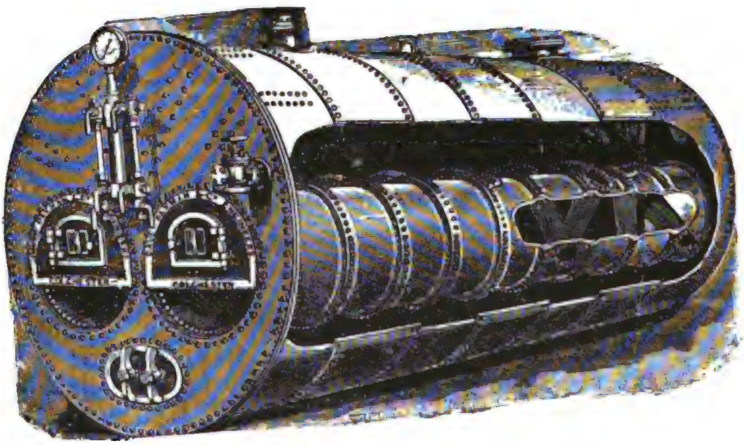

FIG 74.—FLUE WITH RINGS.

Flues of sizes below 5 or 6 inches (1.5 or 1.8 cm.) diameter are not usually riveted up, as is the case with the larger flues, but are commonly drawn in the tube-rolling mill and are known in the market as tubes. The larger mills also often produce drawn tubes, or flues, of much larger size; some, handled by the Author, have been as large as 16 inches (4.9 cm.). In consequence, partly, of such changes in modern facilities for

construction, and for various other obvious reasons, the tubular has very generally superseded the flue boiler. Where still used, it is customary to allow about 12 square feet (1.16 sq. m.) of heating surface per horse-power, and not far from 20 to 1 as the proportion to grate-surface.

Fig. 74 illustrates a case in which the flues are strengthened by rings, placed at the girth-seams joining each adjacent pair of ring-courses.

The domestic make of corrugated flue now used in the "Scotch" marine boiler is illustrated in the following engraving.

FIG. 75.—THE CORRUGATED FLUE.

In this class of boiler it proves particularly valuable, since the construction here met with, of high steam-pressure and

FIG. 76.—FORM OF CORRUGATED FLUE USED AS FURNACE IN MARINE BOILER.

a forced fire, is one which demands strength of structure, and, at the same time, compels the use of thin iron. One objection

to this form of flue is found in its liability to become encrusted with scale or with sediment in the corrugations.

Fig. 76 shows the form given the corrugated flue when constructed for use as a furnace in a marine boiler, and as made by Mr. Fox, who first successfully manufactured them. The joints are welded in a gas-flame, and are usually but little, if at all, weaker than the solid sheet.

For good stationary boilers, according to Cavé,* about 4 pounds of steam may be allowed as the evaporation to be expected per square foot of heating surface (19 kgs. per sq. m.); but this quantity is very variable with the form and proportions of the boiler, locomotive boilers producing several times this quantity, and the amount so evaporated increasing generally as the efficiency of the generator diminishes. The Cornish boiler, as formerly customarily operated, supplied but about one fourth the above-mentioned quantity of steam.

171. **The Cylindrical Tubular** or **Multitubular boiler** like the flue boiler, may be made either with or without firebox; it is now most frequently made "plain," consisting of a cylindrical shell, with plane heads and a "nest" of tubes fitting and nearly filling the water-space up to the water-level. The commercial and accepted rating and proportions of this class of steam-boiler have already been given in § 161. In all important work, the designing engineer will carefully determine the size and economical proportions for the special case in hand. The following may be taken as illustrating the process for this case, as well as for boilers generally:

It is required to design a tubular boiler or a set of boilers capable of supplying steam to a condensing engine of 500 horse-power, guaranteed to demand not more than 22 pounds (10 kgs.) of steam per H. P. per hour, the pressure to be 100 pounds per square inch ($6\frac{1}{2}$ atmospheres), and the feed-water to be taken from the condenser at 120°. Fahr. (48°. 8 C.).

The first step is to determine the quantity of steam to be made. Calculation on the above basis would make it 11,000 pounds (4990 kgs.) per hour, evaporated from 120° Fahr. (48°.8

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* Traité des Machines à Vapeur; Bataille et Jullin.

C.) at 338° Fahr. (170° Cent.) as shown by the steam-tables (Appendix, Table I.). At the customary rating, however (30 pounds or 13.6 kgs. per horse-power), the weight to be evaporated would be 15,000 pounds (6804 kgs.) per hour, and this larger figure is taken as permitting a good margin. Were this evaporated by the best fuel and in a boiler having the efficiency unity, it would require the supply of 1000 pounds (4536 kilogs) of coal per hour.

The financially desirable efficiency of the boiler should be next determined as indicated in the chapter devoted to that subject; it may be here assumed to have been found to be 0.75; and 1333 pounds (6048 kgs.) of fuel would be demanded per hour. By the use of the expression already found (§ 98) we have

$$E = 0.75 = \frac{B}{1 + AR};$$

in which we may take $A = 0.5$ and $B = 1$; then

$$\frac{B - E}{AE} = \frac{F}{S} = R = \frac{1 - 0.75}{0.75 \times 0.5} = \frac{2}{3}, \quad . \quad . \quad . \quad (1)$$

and

$$S = \tfrac{3}{2}F. \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (2)$$

Thus the best ratio of heating to grate surface is twice the number representing in British measures the quantity of fuel burned on the unit area of grate. It thus becomes necessary as a next step to ascertain this last quantity, and therefore to ascertain the height of chimney. This is, in the case of considerable power, as here, to be determined by the principles detailed in §§ 157 and 158. A height of 125 feet may be taken as the result of this investigation. A well-designed chimney of this altitude should permit the combustion of 15 pounds per square foot (7.5 kgs. per sq. m.) of grate with a margin of at least one third for contingencies. On this basis, the

area of grate must be 82 square feet (7.6 sq. m.) and the area of heating surface 2460 square feet (228 sq. m. nearly). This is to be distributed among two or more boilers; since, although a thousand horse-power, even, may be, and sometimes is, obtained from a single boiler, it is usually found inexpedient to concentrate power to such an extent.

A boiler of 5 feet (1.5 m.) diameter and 2½ or 3 diameters long has become a very common and very satisfactory size. This permits a grate of about 30 square feet (2.8 sq. m.), and three such boilers having grates 6 feet (1.8 m.) in length would give the required grate-area with an allowance of ten per cent

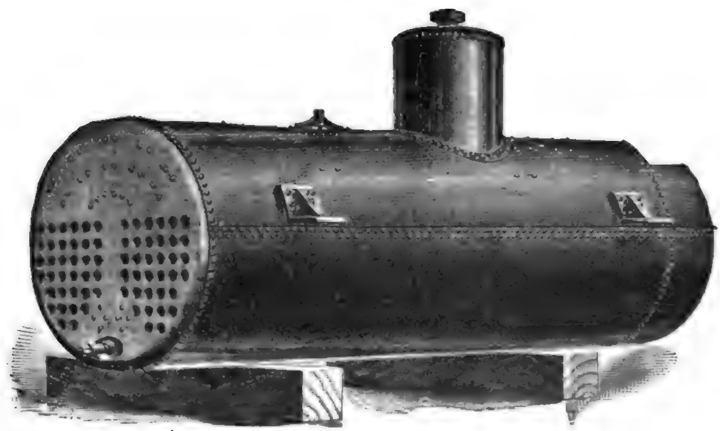


FIG. 77.—TUBULAR BOILER.

for ineffective surface along the edges and in the corners. It may be taken as a good rule to throw in all such differences on the side of increased boiler-power. A boiler of this character with 3-inch (7.6 cm.) diameter of tube will be found to have 63 square feet (5.9 sq. m.) area of heating-surface per unit length, and a length of 15 feet (4.57 m.) gives very exactly the desired total area for a single boiler. The proportion of length of tube to diameter, 60 to 1, is considered a good one, although rather high; and such a boiler operated under the assumed conditions would supply the power demanded with the intended economy of fuel.

The tube-sheets would be made, if of steel, a half-inch (1.27 cm.), or a little less, in thickness, to give good holding power, and the shell, if of metal having a tenacity of 60,000 pounds per square inch (4218 kgs. per sq. cm.), would be, if double-riveted in the longitudinal seams, as in Fig. 77, $\frac{3}{8}$ inch (0.95 cm.) in thickness. The tubes would be 66 or 68 in number, and the braces of sufficient number and strength to sustain the heads safely. The dome would be probably given about one half the diameter of the boiler, and be made of metal rather more than one half as thick, as it would usually be single-riveted.

The tubes should always be placed in vertical and horizontal rows; to "stagger" them would insure a defective circulation and injury to those thus exposed to overheating.

The tubes should never be nearer than 3 inches to the shell of the boiler, and should never be carried down near the bottom of the boiler; but there should be ample water-space at the bottom of the shell. The fire from the furnace first strikes the bottom of the boiler, and there should be a good body of water there.

Pressures have risen in stationary-boiler operation until the common cylindrical tubular boiler of 6 feet (1.8 metres) diameter is made $\frac{1}{2}$ inch (1.27 cm.) in thickness of shell, and is safe, with usual construction, at a pressure of nearly ten atmospheres.

172. Marine Flue-boilers are rarely used at sea, but remain in use on the rivers of the United States. In their design, the same principles which have just been applied are also applicable in the determination of the dimensions of shell and flues. The firebox forms an essential feature of this class, however; and its construction involves calculations of strength of stayed surfaces. In the locomotive, the stay-bolts are placed 4 or 5 inches (10 to 12.7 cm.) apart, but in marine boilers they are more widely distributed, as working pressures are lower. In any case, the area of the flat surface should be estimated, and also the pressure upon it, and a sufficient number of braces used to provide for that pressure. If the braces are of iron of known strength, say 60,000 pounds per square inch (3515 kgs.

per sq. cm.), a factor of safety of 10 would give 6,000 pounds (or 422 kgs.) on each brace of unit section, and the number of braces should be sufficient to safely carry the load on the total surface. The heavier the plate, the greater its resistance to the distorting action of the steam-pressure, and the heavier the stay-bolts and the wider their spacing. In the older forms of marine flue-boiler, in which steam-pressures ranged from 25 to 40 pounds per square inch ($1\frac{2}{3}$ to $2\frac{2}{3}$ atmos.), the stay-bolts were usually spaced from 10 to 8 inches (25 to 20 cm.) apart, and were given a diameter of from one eighth to one tenth those figures. This form of boiler has so generally been superseded by the tubular boiler that it has now comparatively little importance, except on the large rivers. The following are the proportions adopted on board a number of Ohio and Mississippi river steamers, all of which use the lap-welded and drawn tube in place of the older form of riveted flue: A steamer on the Ohio has two boilers, 47 inches diameter and 24 feet long, ten lap-welded flues in each, of 8 inches diameter; two boilers 41 inches diameter, 24 feet long, with six lap-welded flues in each, of 10 inches diameter; steamer Golden Rule, three boilers, 44 inches diameter, 26 feet long, with three 8- and three 10-inch lap-welded flues in each. Such flues are more cylindrical in form than the riveted flue, thereby lessening the chances of collapsing. There are no rivet-heads or laps to interfere with the draught, and consequently the flues are not liable to choke up with soot, are much less apt to scale, and having smooth surface, are much more easily cleaned.

The water-level should be at least 6 inches (2.4 cm.) above the highest flue, and is usually fixed by law or regulation at a minimum of 4 inches (1.6 cm.). The highest line of heating-surface is usually required to be below that level. Where exposed to flame these boilers are not allowed to have a thickness exceeding 0.51 inch (1.2 cm.), and a water-space of at least 3 inches (7.6 cm.) is left between the flues and between flue and shell.

173. **The Marine Tubular Boiler** has now almost universally been brought to a very definite standard form and proportions. It has been already described as consisting of a cylin-

drical shell with plane heads, traversed by large flues and comparatively small tubes, the furnaces being in the flues. Those designed for sea-going steamers are often of very large diameter, the steam-pressures often exceeding ten atmospheres (150 pounds per square inch), they are also made of very heavy boiler-plate. These boilers naturally are oftener double-riveted than those of smaller diameter, and every expedient known to the engineer is adopted to insure safety. Diameters of 15 and even of nearly 20 feet (4.6 and nearly 6 m.) are common, and plates as thick as 1¼ inches (3.2 cm.) have been used. These heavy plates are usually butted at the seams, and the joint is covered with a "butt-strap" or "covering-strip," double-riveted on each side, thus presenting to the eye four parallel rows of large rivets. The calculation of the shell is made in the same manner as in the cases of the forms of boiler already considered. The size is determined partly by the conditions and the method described in § 171, and partly by the necessity of getting the whole set of boilers into a space limited both as to volume and form by the construction of the vessel and by the necessity of economizing as much as possible that space which might be otherwise used for lading and passengers. The stays are usually long rods, extending from end to end in the steam-space, and screwed stay-bolts, reinforced with nuts, in the water-spaces. The dimensions of a steel and of an iron boiler of this class, as actually constructed, are, as given by the builders, the following:

STEEL BOILER FOR 6 ATMOSPHERES (90 LBS. PRESSURE).

Diameter,	16 ft.;	length,	11 ft.;	shell,	⅞ in. thick.
"	4.9 m.;	"	3.35 m.;	"	2.2 cm. "
3 Furnaces,	48 in.	diameter;			17/32 in. "
	1.2 m.	"			1.3 cm. "
250 Tubes,	3¼ in.	"			6½ ft. long.
	7.7 cm.	"			1.98 m. "

Area heating-surface........................	1800 sq. ft.	(167 sq. m.).	
Weight of boiler................	70,000 pounds	(31,750 kgs.)	nearly.
" water.................	50,000 "	(22,680 ")	"
Total weight...	120,000 "	(54,430 ")	"

IRON BOILER (SAME PRESSURE).

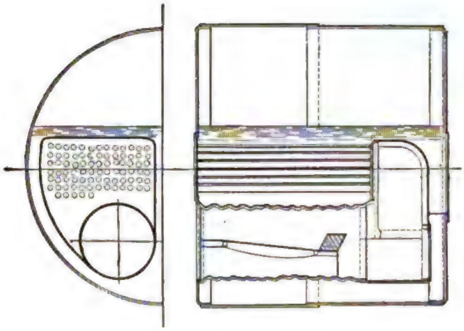
Diameter,	14.75 ft.;	length, 11 ft.;	shell, $1\frac{1}{8}$ in. thick.
"	4.5m .;	" 3.35 m.;	" 2.86 cm. "
3 Furnaces,	39 in. diameter;		$\frac{17}{32}$ in. "
	0.99 m. "		1.3 cm. "
258 tubes,	$3\frac{1}{2}$ in. "		7 ft. long.
	8.9 cm. "		2.1 m. long.

Area heating-surface	2000 sq. ft. (186 sq. m.).		
Weight of boiler	75,000 pounds	(34,088 kgs.)	nearly.
" water	45,000 "	(20,412 kgs.)	"
Total weight	120,000 "	(54,430 kgs.)	"

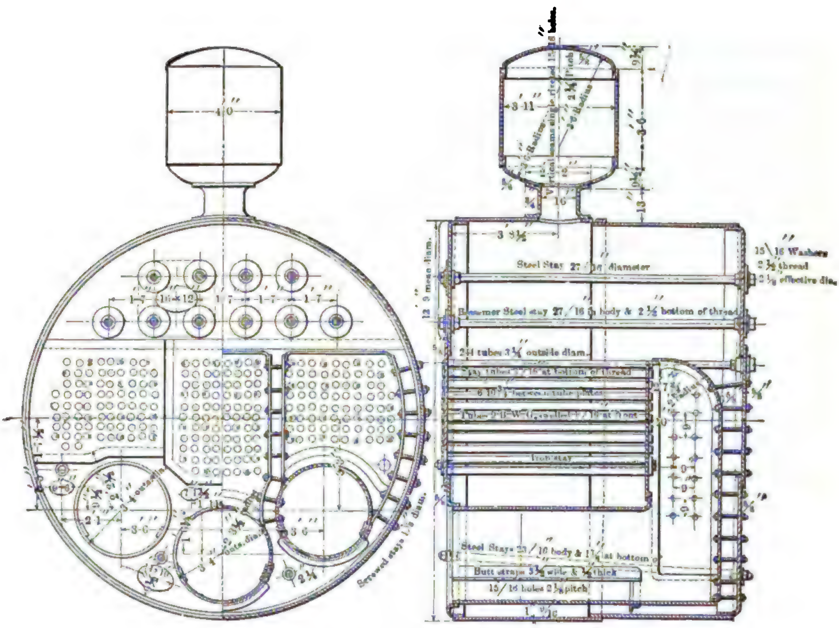
The drawings herewith given, Fig. 78, illustrate the details of this construction. Marine steam-boilers require peculiar care in their design and construction. They must be as light and as small as is possible consistent with the efficiency demanded, and, being exceptionally liable to rapid corrosion and general deterioration, much depends on their being so made as to permit every precaution to be taken to prevent such injury and to insure their preservation. In the construction of cylindrical shells the longitudinal seams are usually all double-riveted, and often even butt-jointed, with double covering strips: this is almost always done in cases in which very high pressures compel the use of heavy plates.

In ordinary practice, the heating-surface ranges from 30 to 40 times the grate-area; the evaporation ranges from 6 or 8 to 10 or 11 pounds per pound of good coal consumed; the crown-sheets are carried as high above the grate as the form of boiler allows; the grate bars are inclined about one in twelve, from front to rear, and are given a length as little more than 6 feet as is practicable. In the cylindrical marine boiler, in which the grates must be set in furnaces which form the lower and larger set of flues, it is not possible to secure either as good a proportion of grate, or as great height above it as is desirable; and the inefficiency sometimes noticed in boilers of this class is commonly due to these faults of the furnaces.

174. Sectional and Water-tube Boilers differ as radically in their design and construction, as in type, from the shell-



Boiler with Corrugated Flue.



Three-furnace Boiler.

FIG. 78.—MARINE STEAM-BOILERS

boilers which have been here considered. As a rule, their design involves but little calculation of strength, as their tubes and connections are always vastly stronger than is absolutely necessary as a mere matter of supporting the steam-pressure. The "headers" or other connections of parts are commonly without rivets, and are fitted, piece to piece, with machine-made "faced" joints, and held in place by bolts. Some special precautions are demanded, in designing this type of boiler, to secure safety against injury, and to avoid serious difficulties arising in management from the comparatively small body of water and of steam carried by them, and the consequent absence of the self-regulating power observed in shell-boilers.

Mr. Robert Wilson states that the following appear to be the points that require special attention in designing these water-tube boilers, to insure their satisfactory working and durability:

(1) To keep the joints out of the fire.

(2) To protect the furnace-tubes from the sudden impingement of cold air upon them on opening the fire-door.

(3) To provide against the delivery of the cold feed-water directly into the furnace-tubes.

(4) To provide for a good circulation to take away the steam from the heating-surfaces.

(5) To provide passages of ample size for upward currents so that they may not interfere with downward currents.

(6) To provide passages of ample size, for steam and water, between the various sections of the boiler, to equalize the pressure and water-level in all.

(7) To provide ample surface of water-level to permit the steam to leave the water quietly.

(8) To provide a sufficiently large reservoir for steam to prevent the water being thrown out by suddenly opening a steam or safety valve.

(9) To provide against the flame taking a short cut to the chimney, and impinging against tubes containing steam only.

The several forms of this type of boiler now becoming familiar have illustrated great ingenuity in securing efficient and novel arrangement of parts, rather than special knowledge of

the character and strength of materials. Some of these forms have been already described, and need not be here further illustrated. This class of boiler is generally in use on land, but attempts have been made to introduce them for marine purposes.

The Author has under his hand sets of drawings of marine tubular boilers for a naval vessel, and of a "sectional" water-tube boiler intended for similar power and the same duty, which afford a means of comparing standard designs of the two types. It does not follow, however, that this comparison would in all cases yield similar deductions.

The tubular boiler has a shell 9 feet (2.74 m.) in diameter, while the other is only 5 feet (1.52 m.). The tubular has 1¼ inches (3.2 cm.) thickness of metal between fire and water where the rear tube-sheet sets into the shell; the greatest thickness in the sectional boiler, between fire and water, is only ⅜ of an inch (9.5 mm.). The shell-boiler has a ratio of grate-surface to heating-surface of 1 to 23, and the ratio of grate-surface to calorimeter is 7.2 to 1; the sectional has a ratio of grate to heating surface of 1 to 41.3, and a ratio of grate-surface to calorimeter of 4.82 to 1, which means the ability to burn more coal per unit of grate-surface.

The steam-space is practically identical in both, but the water in the tubulars weighs 12.6 pounds against 15.5 pounds in the sectional per sq. ft. of heating-surface.

The total iron-work of the tubular boilers is 35½ pounds per sq. ft. of heating-surface, whereas in the sectional it is 25.8. The total weight per unit of heating-surface is as 48 in the former to 41 in the latter. The tabular comparison on page 368 was presented at the same time.

On the other hand, it is objected, by those who oppose the introduction of these boilers on shipboard, that the following considerations are too important to permit their safe employment.*

(1) That they usually occupy as much space as shell-boilers.

* Shock's Steam-boilers, pp. 280–1.

	Shell Tubulars.		Sectional.	
Shell	9 ft. diameter × 9 ft. 7 in. long, ⅝ in. thick.		5 in. diameter × 20 ft. long, ⅝ in. thick.	
Heads	⅝ in. thick.	To carry 115 lbs.	⅛ in. thick.	To carry 150 lbs.
Seams in fire	1¼ in. thick.		None	
Heating-surface	1322.7 sq. ft.		3100 sq. ft.	
Grate-surface	57.3 sq. ft.	Proposed battery, 14 boilers, 18,517 sq. ft. heating-surface, 802 sq. ft. grate-surface. Fire-rooms, 9 ft. 6. in. wide. Coal passed through whole length of fire-room.	75 sq. ft.	Proposed battery, 8 boilers, 24,800 sq. ft. heating-surface, 600 sq. ft. grate-surface. Fire-rooms, 12 ft. wide. Coal passed through 3 ft. passage-way.
Ratio of grate-surf'e to heating-surface.	1 sq. ft. to 23 sq. ft.		1 sq. ft. to 41.3 sq. ft.	
Steam-space	169 cubic ft.		392.6 cubic ft.	
Ratio of steam-space to heating-surface.	.012 cubic ft. per 1 sq. ft.		.012 cubic ft. to 1 sq. ft.	
Water, weight of	16,660 pounds		48,262 pounds	
Weight per sq. foot heating-surface	12.6 "		15.5 "	
Iron-work, weight of	47,040 "		80,221 "	
Iron-work per sq. ft. heating-surface	35.5 "		25.8 "	
Total weight	63.700 "		128,423 "	
Total weight per sq. ft. heat-surface	48.18 "		41.44 "	
Calorimeter	8.27 sq. ft.		18 sq. ft.	
Ratio of grate-surface to calorimeter.	7.2 to 1 sq. ft.		4.82 to 1 sq. ft.	
Height of water-line above crown-sheet.	6 in.		24 in.	

(2) That they are subject to rapid and serious fluctuations of water-level and steam-pressure.

(3) That the circulation is less free and steady.

(4) That, for the above reason and because of their liability to accumulation of incrustation, overheating is sometimes peculiarly apt to take place.

Notwithstanding these objections, which are undoubtedly to a certain extent valid, these boilers are thought likely, by many engineers, to find their way into use at sea.

Every good "sectional" boiler consists of a system of water-tubes, or their equivalent, so arranged as to permit a rapid, steady, and certain circulation; a system of "headers" or connections by which the steam and water find their way into the steam-space, where separation and settling may occur; and of this steam-space, usually in the shape of a large drum or set of drums of small section from which the steam is discharged, dry, into the steam-pipe, and by it conveyed to the point at which it is to be utilized. In some cases, the steam-drum is also partly a water-reservoir, and thus assists in producing a regularity of operation very difficult to secure unless obtained by the presence of a considerable body of water, somewhere in the structure. In this last case, the greatest care must be taken to

secure this drum against the direct action of flame, the nest of tubes being ordinarily so disposed as to intercept the gases leaving the furnace.

175. **Upright and Portable Boilers** are chosen when the location or use is such as demands concentration of space or facility of transportation. The upright boiler, occupying little floor-space, having, for the small powers for which it is most commonly used, no great height, and being self-contained and thus requiring no setting, is a form that meets these special conditions most perfectly. Its design is precisely that, in method, of the cylindrical tubular boiler, except that it must have a firebox. The latter is made in the form of a short cylindrical, upright, flue, occupying so much of the lower part of the boiler as will give the needed height of furnace and ash-pit. The water-space between this flue and the shell is usually about one tenth the diameter of the latter.

In the design of this flue or furnace, care should be taken to introduce stay-bolts to prevent collapse from overpressure or weakness produced by corrosion, a method of yielding which causes the greater proportion of explosions of boilers of this kind. The thickness of furnace sides is commonly the same as that of the shell; the bottom ring and the tube-sheet, at its upper end, giving additional security and making the furnace very much safer against accident so long as it is in good order. The calculations of this detail are the same as for any other cylindrical flue subjected to external pressure.

The steam-space in the upright boiler, as often built, consists only of the volume of the upper part of the boiler above the water-level, and as the tubes occupy a considerable proportion of the total volume of the shell, the steam-space is correspondingly restricted. This extension of the tubes above the water-level to the upper tube-sheet also renders their upper ends liable, at times, to injury by overheating. A better plan is that shown in § 15, in which the upper tube-sheet is sunk below the water-level, and all the steam-space needed is obtained by carrying the shell upward to any desired additional height, and connecting the two by a frustum of a cone having its upper end no larger than is needed for the chimney-flue; the tubes

are thus protected, and the steam-space made ample. The same remarks apply to the computations of this cone as to those of the furnace; it is, however, of stronger form and less likely to require staying.

The Portable Boiler is sometimes upright, as when used by itself independently of the engine, or when it has to carry the frame of an upright engine; or it is horizontal, if of large size, or if forming the bed-piece of a horizontal engine, as is a more common arrangement. In either case, no very important difference arises in either the design or method of construction, except that somewhat greater care is taken to make it safe against injury either by transportation or by the stresses coming of the action of the attached machinery. It is always better that the boiler should carry an engine with its frame than that it should itself act the part of that member. In all cases, the connection of engine and boiler and of boiler with its carriage, where locomotive, should be so arranged that the changes of form and dimension due to variations of temperature and the stresses caused by difference of temperatures of adjacent parts as well as changes of pressures may have no ill-effect.

A good steam-drum or dome is of even greater advantage on the portable than on the stationary boiler. Their attached engines are usually wasteful, take steam in very variable quantity, and are peculiarly liable to cause "foaming."

The following are the proportions adopted for portable engine-boilers by a well-known firm of British builders: *

PORTABLE ENGINE-BOILERS.

Horse-power.	Heat-surface—Square Feet.				Grate-surface.		Grate-surface.	Tubes.	Horse-power.
	Fire-box.	Tubes.	Total.	Per Horse-power.	Total.	Per Horse-power.	Heat-surface.	Draught-way—Sq. ft.	
5	19.6	81.8	101.4	20.2	3.6	0.72	28.2	0.66	5
10	32.4	161.9	194.3	19.4	6.2	0.62	31.1	1.08	10
15	43.0	228.7	271.7	16.9	8.6	0.53	31.6	1.39	15
20	53.0	279.2	332.2	16.6	10.5	0.52	31.7	1.60	20
25	59.3	346.5	405.8	16.0	12.8	0.51	31.8	1.87	25
30	68.1	408.8	476.9	15.9	14.9	0.49	31.9	2.35	30

* Wansbrough, p. 81.

A source of danger to which the upright boiler is peculiarly liable is that of "burning" the firebox or tube-sheet in consequence of the collection of sediment in the water-legs about the furnace or on the lower tube-sheet. The water-leg is sometimes found filled with solid matter, and the tube-plate so heavily incrusted that the metal is readily overheated and burned. All boilers of this kind should be provided with hand-holes at the level of the crown-sheet of the furnace, and so placed as to permit thorough inspection and complete removal of the sediment at frequent intervals.

Comparing the vertical with the horizontal tubular boiler, it will be observed that a large item of expense is avoided in the cost of setting; and that an incidental advantage is secured for the former in the fact of its accessibility at all times, whether working or cold, for examination of the exterior. The upright boiler is also less liable, while in operation, to injury from a small depression of the water-level; the fire never comes in contact with its shell, and this permits the safe use of plates as heavy as may be desired; no strains from unequal expansion are to be apprehended, and experience shows this to be an element contributing to the exceptional durability of this class of boiler. Its only setting is a foundation with an ashpit, and its connection to the chimney-flue. In the vertical tubular boiler, loss of water, and the falling of the water-level even a considerable proportion of the whole depth of boiler, does not necessarily involve danger; and the upper part of the tubes may be utilized as superheating surface, and the extent of the superheating adjusted very conveniently by varying the water-level.

Where the feed-water is not very pure, however, the great and often fatal objection to this form of boiler arises in the danger of sediment or scale being deposited on the lower tube-head, the furnace-crown, and introducing danger of overheating and of explosion. A considerable proportion of the explosions of this kind of boiler, which have been investigated, are known to have been due to this cause.

176. "Locomotive" Boilers whether stationary or actually forming a part of the locomotive, are of the same general design and construction. They consist of a horizontal, cylindrical,

tubular boiler, crowded, as far as is safe and practically economical, with tubes, and with a firebox added as an integral part of the structure. In such boilers, designed to be stationary, the tubes are often larger than those adopted in the boiler of the locomotive, as the draught is commonly vastly less intense, and the power demanded also comparatively small. The boiler of the locomotive represents the highest art of the engineer in the combination of the essential desiderata for its purpose: great power in small weight and volume, combined with maximum economy of fuel consistent with such concentration of power.

The locomotive must always use steam of maximum pressure, must use enormous quantities because of its necessarily great power, and must be at once safe and fairly economical. In consequence of its exposure to the action of its own great inertia in its constant motion over, often, an irregular roadbed, and because it must sustain the stresses due to the action of its own machinery and to frequent collisions, of greater or less violence, while making up and transporting trains, the whole structure must be designed with especial regard to such extraordinary and unreckoned strains as may be thus caused. Since the power demanded is a maximum, the tubes must be as numerous, and therefore as small and as closely packed, as is possible without affecting sensibly the circulation of water and thus losing steaming capacity; and since economy of fuel is hardly less important than steaming capacity, the tubes must have sufficient length to give a ratio of area of heating surface to weight of fuel burned such as will insure that efficiency found to be practically desirable. With all this, the designer must keep in mind the special necessity of compactness of structure, and of a limit in weight fixed, in many cases, at least, by the magnitude of the friction on the rail and the tractive power demanded by the special kind of work for which the engine is intended. To reconcile so many and oftentimes conflicting conditions, and to secure a maximum total efficiency, is evidently a problem of immense importance and of corresponding difficulty, and one which can only be fully solved by the gradual evolution of the precise

form and proportions best fitted for each of a number of specialized types and duties, such as is illustrated by the different passenger and "freight" or "goods" engines now becoming standard.

The methods of computation of size and strength of parts are in no way peculiar, and no special consideration of them is here demanded. Custom guided by experience has led to the production of such proportions as are illustrated in standard practice.

Common faults of design in this, as in other forms of horizontal tubular boilers, are the excessive crowding of tubes and serious contraction of the water-spaces about the furnace. It would probably be found advantageous not only to preserve good water-channels between adjacent tubes, but to leave out a vertical row of tubes along the diameter of the boiler, and to allow an equal space between the nest of tubes and the shell all around. This has often been done by good constructors, with evident advantage, when boilers are doing much work. It is a safe arrangement to adopt for all cases. Water-legs should be made to widen from the bottom upward.

The crown-sheet is supported by girders, "crown-bars," resting at each end on the upper edge of the side sheets of the furnace and carrying the load by stays set at frequent intervals in their length. They should be very carefully designed. Stays to the shell are unsafe.

The material used in this class of boiler is becoming universally soft steel, containing so little carbon that it will not temper. Harder steels crack in the firebox-sheets, especially where deep and hard-worked. The thickness of the shell is often reduced 15 or 20 per cent, as compared with iron. Good steel neither cracks nor blisters. As a rule, with steam at 120 pounds, the general practice is, in the United States, to use $\frac{3}{8}$-inch iron or steel for outside sheets, $\frac{5}{16}$ inch iron or steel for fireboxes, and from $\frac{3}{8}$ to $\frac{1}{2}$ inch for tube-sheets. Water-spaces around firebox from $2\frac{1}{2}$ to $3\frac{1}{2}$ inches inside, and from $2\frac{3}{4}$ to 4 inches in front. At straight seams $\frac{11}{16}$ inch rivets are used, spaced $1\frac{3}{4}$ inches between centres. Longitudinal seams double-riveted, centres of the two lines of rivets $1\frac{1}{8}$ inches apart, centre to cen-

tre of rivets on same line 2¾ inches. Stay-bolts ⅞ inch diameter, 4 inches centre to centre. It is thought that thin plates give the best result in fireboxes, sides and back of ¼-inch steel, crown-sheet $\frac{5}{16}$-inch steel, and tube-sheet ⅝ inch. Tube-sheets of $\frac{7}{16}$-inch iron, the other plates being steel, have also given good results. It is believed that ¼-inch steel plates are strong enough for side sheets and less liable to crack than thicker plates. Crown-sheets are more easily straightened when sagged down from mud collecting, and will not crack so quickly from overheated crown-bar bolts.

The life of a good boiler is usually from ten to twelve years. Tubes are removed to permit inspection every three or four years. Steel and iron are now used for wood-burning fireboxes, with a result usually declared to be in favor of steel, in consequence of the lighter sheets and the metal not blistering. With bituminous coal copper, steel, and iron are used. Copper will not crack, but wears away, and is soon reduced to a dangerous thinness. A copper firebox lasts from three to five years. The objection to iron fireboxes is that the iron blisters, becomes "burnt" and very brittle, and cracks. Three years is the average life of an iron firebox. The only objection to steel is that it sometimes cracks. The average life of the best is 9 years and 6 months; of the worst, 4 years and 4 months; of the total reported, 6 years and 4 months.

The following is considered a good specification for a steel locomotive boiler:

Boiler to be made of mild steel $\frac{7}{16}$ inch thick, riveted with ¾-inch rivets placed not over 2⅛ inches from centre to centre; all horizontal seams and junction of waist and firebox double riveted; all longitudinal seams provided with lap welt, with rivets alternating on both sides of main seams, to protect calking edges, and all parts well and thoroughly stayed; top and sides of outside firebox all in one sheet; back-head a perfect circle. All plates planed on edges and calked with round-pointed calking tools, insuring plates against injury by chipping and calking with sharp-edged tools. Boiler tested with 180 lbs. to the square inch, steam-pressure. Waist 52 inches in diameter at smoke-box end, made wagon-top with extended arch with

one dome 30 inches diameter on the wagon-top; tubes of charcoal-iron, No. 12 B, wire-gauge, 200 in number, 2 inches outside diameter and 11 feet $8\frac{3}{4}$ inches in length, with copper ferrules on firebox end; firebox made of mild steel, 78 inches long and 34 inches wide; all plates thoroughly annealed after flanging; side $\frac{5}{16}$ and back-sheets $\frac{3}{8}$ inches thick; crown-sheet $\frac{3}{8}$ inches thick; flue-sheet $\frac{1}{2}$ inch thick; water-space 5 inches wide at sides, $3\frac{1}{2}$ inches wide at back, and $3\frac{1}{2}$ to $4\frac{1}{2}$ inches wide at front; stay-bolts $\frac{7}{8}$ inch diameter, screwed and riveted to sheets, and not over $4\frac{1}{4}$ inches from centre to centre; fire-door opening formed by flanging and riveting together the inner and outer sheets; 2 rows of hollow stay-bolts above fire; 2 rows of telltale stay-bolts at top on sides; crown supported by crown-bars, each made of two pieces of $5 \times \frac{5}{8}$ inches wrought-iron; placed not over $4\frac{1}{2}$ inches between centres, bars to extend across, with ends resting on castings on the side-sheets; crown-bar bolts $\frac{7}{8}$ in. diameter, with flat heads under the crown-sheet, the fit in the crown-sheet to be tapered and drawn to its place by a nut above the crown-bar; the crown to be well and thoroughly stayed by braces to dome and outside shell of boiler; cleaning holes in corner of firebox, and blow-off-cock in side; smoke-stack straight; grates cast-iron, rocking with dump; ash-pan wrought-iron, dampers front and back; balanced poppet throttle-valve of cast-iron in vertical arm of dry-pipe.

The firebox first introduced by Mr. Wooten on the Philadelphia and Reading Railway is carried higher than ordinary, so as to obtain room for broadening the grate and thus enlarging it, so as to be capable of successfully burning the hitherto useless anthracite culm. The dimensions of their common locomotive firebox are 60 and 66 by 32 inches; the first of new design is 8 feet 6 inches long by 7 feet $6\frac{1}{2}$ inches wide; the heating-surface of the firebox is 106 square feet, and of the combustion-chamber 26 feet, making a total of 982 square feet. The grate-rest is between water-bars to prevent burning out, and the area is 64 feet. The consumption of coal is only 16 pounds per hour per square foot of grate-surface against 40 to 60 pounds in the ordinary locomotive.

The fuel remains perfectly quiet in the firebox, the consump-

tion is slow, the steam is more freely made than in the common style of locomotive boiler, and no smoke or sparks are ejected from the smoke-stack.

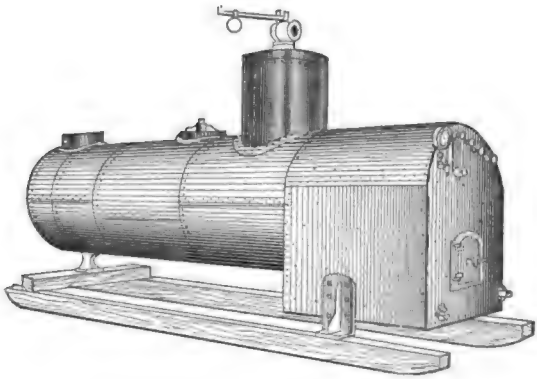


FIG. 79.—STATIONARY "LOCOMOTIVE" BOILER.

The stationary boiler of the locomotive type is shown in the accompanying figure, as customarily mounted on skids for transportation, with gauge-cocks, water-gauge, steam-gauge, and safety-valve attached, and in working order.

CHAPTER IX.

DESIGNING ACCESSORIES—SETTING—CHIMNEYS.

177. **The Setting of Boilers** which are not self-contained involves the construction of a system of side-walls and bridge-walls, customarily of brickwork, and entails so great an expense as often to make the question of the adoption of the firebox or

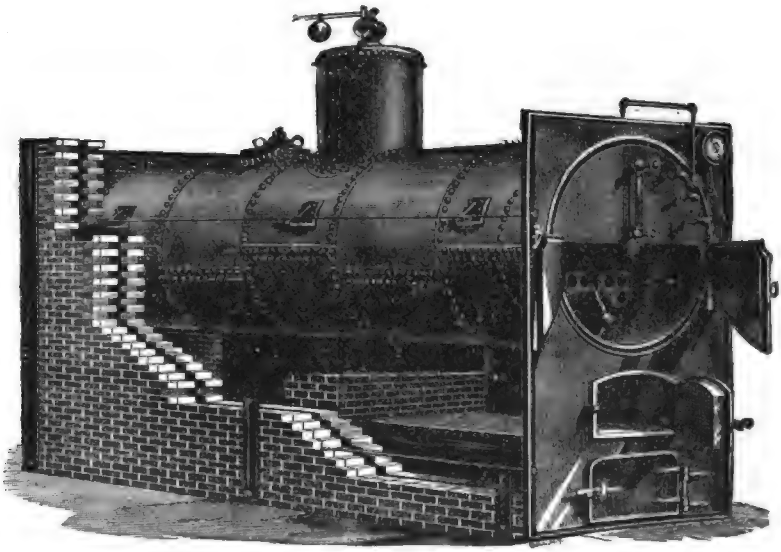


FIG. 80.—SETTING OF TUBULAR BOILER.

the plain boiler one of serious importance. It is usually found to be economical to adopt the firebox boiler for small powers, and to employ the other type where large quantities of steam are to be made.

The form of the setting, the arrangement of bridge-walls, and the number, size, and disposition of flues, are all matters of ready determination once the style of boiler is settled; but while the best engineers have come to a nearly uniform and

standard design, a great variety of forms and proportions are actually in use for every one of the familiar boilers. General practice prescribes the use of a cast-iron front protected from the action of the fire by a fire-brick lining. Side-walls are of red or common brick, lined with fire-brick wherever exposed to the direct action of the flame. The bridge-wall adjacent to the furnace is of fire-brick, except in parts so located as to be protected from the impinging flame; and the flues, even, are sometimes similarly lined. The brickwork is held in place and the whole structure kept together by tie-rods and binding-bars, of which the fastening bolts are so located as to be exposed only to moderate temperatures.

The following figure illustrates such a setting for a horizontal tubular boiler of good proportions:

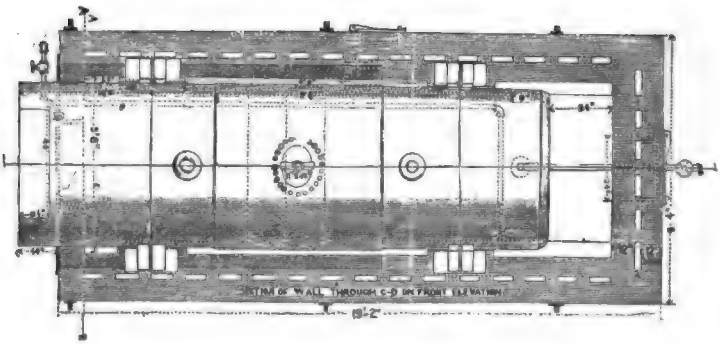


FIG. 81.—SETTING OF HORIZONTAL TUBULAR BOILER.

Here a set of 12-inch-side walls are lined with an inner wall, and an air-space between intercepts the heat, and is itself partly or wholly of fire-brick. Vertical binders on each side, tied together by heavy transverse bolts at top and bottom, hold all in place; and similar bolts tie the front to the rear wall. The bridge-wall is set inside, at the rear of the grates, and is raised just high enough to prevent fuel falling or being thrown back under the boiler.

The practice of the Hartford Boiler Insurance Co. is illustrated by the next figure, in which are given the dimensions of setting for a "60-inch" tubular boiler, as published in the speci-

fication. In this sketch the fire-brick used in lining the walls is sharply distinguished from the remainder.

Where no circulation is permitted there is no objection to allowing the spaces above and below the boiler to communicate. In some cases the space above the boiler, when closed in, is used as a flue, with the effect of drying, and sometimes of superheating, the steam. There is an unquestioned advantage in keeping the boiler as nearly of uniform temperature as possible; but many engineers consider this system to involve some risk. The suspension of the boiler is a matter demanding the greatest care. It was formerly the custom to pay little attention to this matter; but the occasional explosion of a boiler in consequence of irregular strains so induced, has led to more

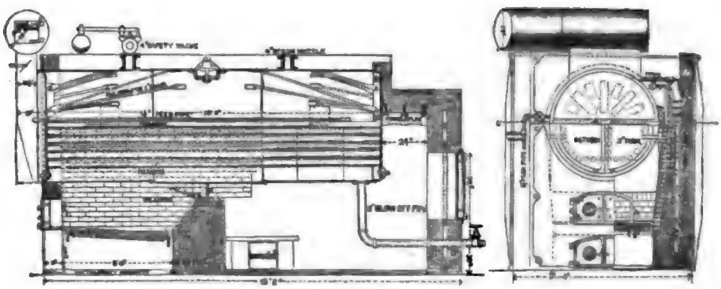


FIG. 82.—SETTING OF TUBULAR BOILER.

careful design. The most common system is probably that in which the boiler has a set of cast-iron lugs riveted on its sides and resting on plates built into the brickwork of the side-walls, thus distributing the weight. In some cases the boiler is suspended from transverse girders resting, at each end, on the side-walls of the setting; and the heads of the supporting bolts have sometimes been carried on springs to insure an equalization of load and its uniform and safe distribution—which is the essential aim of all good systems of support. Where two points of support are chosen on each side, they should be placed one fourth the length of the boiler from each end; where three supports are introduced, the outer ones should be one sixth the length of the boiler from the ends, and the third should be

placed in the middle, thus giving a uniform load on all. Horizontal boilers are sometimes supported at the rear end on plates resting on rollers to reduce frictional resistance to change of dimensions.

It is probably as well not to attempt to carry the weight of the boiler on the walls of its setting, and this can be avoided by adopting the plan of inserting vertical posts, made of a pair of channel-bars secured back to back, and thus forming strong, simple, and inexpensive columns, on which the load can be safely and permanently carried. The air-space between the walls is an important safeguard against injury by the change of form of the inner wall with variation of temperature. Where desirable, the space between the boiler and this continually moving mass can be closed by carrying a flange of angle-iron along it, and supporting this flange from the iron posts in the walls. Angle and channel irons are also best for use in making the binders or "buckstaves" by which the whole setting is kept in shape. Where cast-iron is used at all, as in the fronts, it should be heavy enough to keep its shape.

Where a boiler is supported by lugs riveted to its sides and bearing on the side-walls of the setting, the principal risk is usually, probably, that of the failure of the riveting. The boiler-shell has a large margin of strength, and no injury need ordinarily be feared from the stress coming of its own weight between the points of support. When the rivets are placed not more than four or five diameters apart, the boiler may be considered as perfectly safe, the workmanship being good. It is advisable to place covering strips on the inside to take the heads of the rivets securing the lugs in place.

178. **Forms of Covering** to prevent the loss of heat from the boiler and flues by conduction and radiation are of considerable variety. The rudest, though an effective one, is a layer of ashes over the top of the boiler, filling in between the side-walls of the setting. This is often objectionable, as giving rise to annoyance from dust; and various mineral and fibrous substances are preferred, such as asbestos, hair-felt, and several kinds of plaster and cement. Where hair-felt is used, it is often covered with canvas to give a neater appearance, and to

protect the felt from dust and injury. Occasionally, a brick arch is turned over the whole structure, and the air-space so produced relied upon to intercept heat. This construction is probably not quite as efficient as the other coverings, but it has the advantage of permitting easy access to the boiler for inspection and repair. A loose blanket is as good.

179. **The Form of the Bridge-wall** is not always the same in the same general design. A bridge-wall is needed at the rear end of the grate, and it is now rather unusual to build others; but two, or even more, are sometimes introduced for the alleged purpose of securing intermingling of the currents of furnace-gas and their contact with the boiler. In some cases the bridge-wall is carried up to the boiler-shell nearly, and fitted rather closely to its form; a more approved system, however, gives its top a perfectly straight and level line. Ample space should always be allowed for the passage of the gases, as well as above the grates, for the completion of combustion. The semi-diameter of the boiler is none too great for the depth of this latter space. Two feet is a good minimum.

180. **The Disposition of Flues** is subject to the same remark as was made relative to the bridge-wall. No standard practice can be described; but it is continually becoming more usual to leave the whole space beneath the boiler without subdivision from bridge-wall to chimney-flue, taking off the gases from the tubes as directly to the chimney as possible, and controlling the flow of the gas-current by the damper. Occasionally a special direct flue is provided with its own damper, when a drop flue is ordinarily used, or when the flame is carried over the shell, the former being opened when the fires are started to secure rapid kindling, and closed again when the fires are fairly burning. The shortest line of flue from the boiler-setting to the chimney is best in all cases.

181. **The Location and Design of Chimney** may often be the first step to be taken preliminarily to designing the boiler; or, as is oftener the case, the user purchases his boiler and then erects such a chimney as the designer and vender may recommend, in such location as he may find practicable. In many cases the chimney consists of a simple pipe of sheet-iron, ris-

ing directly from the flue, which, forming part of the boiler setting, also serves as the base of the pipe. In this case the rules for proportioning are to be taken as those governing marine practice, and the draught as calculable on that basis, with a considerable margin to allow for variations of temperature, humidity, and mobility of atmosphere. In the majority of cases, however, a chimney-stack of brickwork is preferred, both on the score of permanence and on that of better draught; the iron flue permitting a loss of heat and cooling of the air-column, which does not take place to any observable extent in the brick stack. No. 10 or 12 iron is ordinarily used.

The essentials of a good design are: adaptation in draught power and capacity, in height and area of flue, to the precise conditions to be met, with ample surplus for emergencies; a solid and perfectly safe foundation; a well-formed, straight, well-proportioned shaft; stability against the pressure of the most violent winds; security against injury by its own heated gases; and economy in construction and maintenance. The first two of these requirements are met by the methods already detailed in § 160: a safe foundation is obtained by going down to the rock wherever possible, or to firm, compact, stable soil, and there starting the bed courses, giving them ample area to carry the superincumbent weight safely. Where difficulty is met with in the endeavor to accomplish this, a broad concrete base is often laid on the yielding substratum of soil, and on this the masonry is laid up after ample time for hardening and settling is allowed. The more slowly the construction is carried on, the better the result. The form and proportion of the shaft is partly a matter of taste, judgment, and architectural effect, and partly of calculation based on the elements prescribed by the conditions under which the boiler is to be operated. Stability is assured by carefully proportioning weight of stack and breadth at the foundation to meet the overturning force of the highest winds, and allowing, further, a fair factor of safety. A pressure of 55 pounds per square foot (268 kgs. per sq. m.) on chimneys of square section, and one half this amount on chimneys of circular or octagonal section, is a common assumption as a measure of the maximum force of

the wind in exposed situations. In sheltered localities, a calculation of stability is rarely made. Security against the cutting or overheating which may sometimes occur where the furnace gases reach the chimney at a very high temperature is obtained in large chimneys by the construction of an inner chimney of fire-brick, separated from the main structure by a narrow air-space. In small chimneys a lining of fire-brick built into the walls of the chimney for some distance upward from the base is the usual safeguard, and even this is often omitted. Economy is obtained by making the design as simple, the height and the dimensions generally as small, as may be consistent with a good design.

Circular and octagonal sections are best as a rule, but the square section is usually the least costly to build. Where an outer and an inner shell are put up separately from the foundation, provision is often made to cover, in some way, the annular opening between the two at the top of the inner stack to prevent the settlement of dust between them: this is not, however, usual or essential; but a cleaning door should be placed at the bottom, through which access can be had both to this space and to the main flue. All the talent of the architect is often demanded in the design of the exterior of large chimneys.

The following are the dimensions of a large chimney of good design:*

Height above grade	192 ft.	58.5 m.
Total height (with foundation)	204 ft.	62.18 m.
Batter	2 in 100, nearly.	
Diameter at grade	17 ft.	5.18 m.
" of flue at top	8 ft.	2.43 m.
Thickness, stack	2.67 to 1.33 ft.	0.8 to 0.4 m.
" inner shell	1.33 to 0.67 ft.	0.4 to 0.2 m.
Weight	2,187 tons.	2,222 tonnes.
Horse-power	2,700.	
Cost per H.-P	$5.53.	
" total	$14,000.	

182. Steam and Water Pipes and their connections should be as carefully designed and located as the members of the

* *Sci. Am. Supp.*, Jan. 29, 1887.

structure itself. Steam should be taken off at the point at which it will pass out most perfectly dry, or, if provision is made for it, superheated. If a steam-dome is attached to the boiler it should usually be placed at a distance from that part of the steam-space into which steam is rising most rapidly, and the steam-pipe should be led from the highest point within it. If a dry pipe is used it is better to so place it that its most contracted openings are nearest the furnace. Such area should be given this pipe that the frictional resistance to flow should not sensibly reduce its pressure, and the same precaution should be taken in placing valves. A velocity of 6000 feet (1829 m.) per minute should usually be a maximum rate of flow.

The steam-pipe should be as carefully protected by non-conducting covering as the boiler itself, and it should be so set and drained that no water can collect at low points or in angles, to be thrown forward by the steam into the engine, there to cause danger of accident. The Author has frequently known this to occur, and the steam-pipe itself is sometimes burst open by its impact, causing loss of both life and property. Experiments conducted by the Author* have shown that pressures produced by this so-called "water-hammer" may amount to probably above ten times that which the pipe was expected to sustain in regular work. Drain-cocks and steam-traps suitably placed may be used to take away water collecting in bends where they are unavoidably introduced. Care must be taken, in long straight lines of pipe, to avoid danger of injury by the expansion and contraction taking place with change of temperature as the pipe is heated and cooled when steam is sent through it or when emptied. Where precautions are not taken, as in the introduction of bends, angles, or slip-joints or their equivalents, pipes are sometimes broken, joints are set leaking, or connections are completely broken, and serious results follow. If extensive systems of pipe are properly guarded against water-hammer and excessive temperature-strains by correct location, thorough drainage, and good designing, no other danger than that of corrosion is to be apprehended.

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* Trans. Am. Soc. Mec. Engs., vol. iv., 1882–83. p. 404.

Similar principles control the location and proportioning of feed-water pipes. They should be of ample size and strength, should be so located as to be free from liability to injury by expansion and contraction, and should be led into the boiler in such manner and should so discharge the feed-water that injury should not be done the boiler by the impinging of cold water on heating-surfaces, or by the collection of a mass of cold water at times in the lower part of the boiler, thus introducing serious strains, along the line separating the cold from the hot water, or elsewhere. The entering feed should be warmed by flowing out into the general mass of circulating liquid, and should not be so directed as to impinge on metal. No calculations of strength of ordinary steam and water pipe are ordinarily made, as the internal pressure is usually the least important stress affecting them. If strong enough to bear other stresses and thick enough to resist corrosion for a considerable time, they are amply strong.

All cocks, valves, and connections should be strong enough and sufficiently well put together to bear safely such accidental stresses as have been referred to without risk.

183. **Safety-valves** are absolutely essential to every steam-boiler. Many explosions have been known to have been caused by the failure of a safety-valve to open at the intended pressure, and it is considered good practice to evade such a danger by introducing two safety-valves into the design of every boiler.

The office of a safety-valve, as used on a steam-boiler, is to discharge steam so rapidly, when the pressure within the boiler reaches a fixed limit, that no important increase of pressure can then occur, however rapidly steam may be made. It has also another office: it should be so constructed and arranged that should any accident occur it may be opened by hand and the steam-pressure lowered very rapidly, even when the fires in the boilers are burning brightly and generating steam with maximum rapidity. The size of a safety-valve is determined by the character of the valve itself, by the pressure at which the steam is to be discharged, by the difference permissible between the pressure at which the valve is to open automatically, and that

at which it is intended to be capable of discharging steam as fast as the boiler can make it.

A valve of defective design or badly constructed must necessarily be larger, to do the same work, than one of similar type well designed and constructed. Steam is discharged at any given rate through an orifice of smaller dimensions as the pressure increases; the lower the pressure, on the other hand, the larger must be the valve. A boiler in which steam is carried at ordinary pressure may require a safety-valve of large area, while the same quantity of steam would escape through a rivet-hole in a boiler containing steam at pressures such as were attained by Perkins and Albans a generation ago.

Rules by which to calculate the proper area of safety-valves for every case arising in his practice are used by every engineer accustomed to designing steam-boilers. These rules vary considerably with differences in the experience or the judgment of their authors.

But a safety-valve, as has been stated, should be capable of discharging very much more than the maximum quantity of steam that the boiler can make when doing its best. The valve must be raised, ordinarily, by the action of the steam itself, and the force exerted by the steam-pressure upon its disk rapidly diminishes as it rises from its seat. The seat is bevelled, too, in such a manner that the effective area for discharge of steam is but a fraction of that due the rise of a valve having an unbevelled seat. It is therefore advisable to give a very large area to the valves.

It has been common in the United States to allow but one square inch of area of valve-opening for 25 square feet of heating-surface, or a ratio of 0.0003, nearly; while another rule gives one square inch to three feet of grate-surface: an English rule allows an area equal to a half square inch to a square foot of grate, or 0.003 the grate-surface, nearly; while still another authority nearly doubles this area of valve. But the area should always be based on the quantity of steam made. The Author has been led by experience to adopt the rule: Multiply the maximum weight of steam which the boiler is expected to generate per hour by five and divide by ten times the gauge-

pressure, increased by ten, in British measures; or, divide that weight by twice the latter quantity. Thus,

$$a = \frac{0.5w}{p+10};$$

where w is the maximum weight of steam made per hour in pounds, p the pressure in pounds on the square inch, and a the area of the valve-opening in square inches.

For important work it is advisable, especially for large boilers, to calculate carefully the area of opening needed, by the principles controlling the discharge of steam from orifices. A very large excess over the area demanded to just discharge steam at the maximum rate at which it is made should be given, as it is often necessary to rapidly reduce pressure just when the fires are brightest and vaporization most active. The design of the valve is rarely a problem solved by the designer of the boiler. Valves in great variety are made and sold by manufacturers, and it is customary to purchase such as are needed.

One of the simplest of the common form, of lever safety-valve is that seen in Fig. 83, in which the valve, A, is held down to its seat by a lever, BC, having a fulcrum at the pin, C, and resting on the valve at D. The weight, W, can be adjusted at any distance from D that may give the moment required to resist the intended steam-pressure. A guide at E, secured, like the pivot standard F, to the valve-chamber, G, keeps the lever in the designed vertical plane. The size of the valve is usually reckoned as that of the opening, H, of pipe and valve-seat. A "feather" on the outer side of the valve guides it and ensures its return fairly upon its seat when it falls with reduction of pressure. Fig. 84 shows the exterior of a better and more recent type of lever safety-valve. In some cases weights are carried directly on the top of the valve-

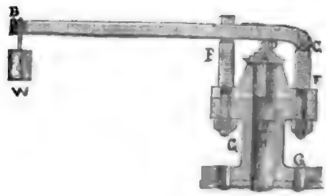


FIG. 83.—LEVER SAFETY-VALVE.

stem, a spindle rising from the latter over which they are threaded; the pressure is then determined by adding or removing weights. In other instances the weights are suspended below the valve and inside the boiler, the idea being to make

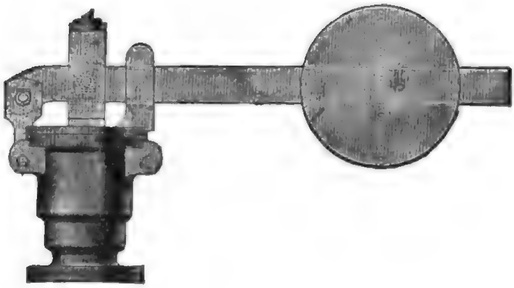


FIG. 84.—SAFETY-VALVE.

them inaccessible to any one, except at times when no steam is on and when the inspector may adjust them. Often valves are so constructed that, once adjusted, they may be locked up, and thus made safe against the tampering of irresponsible or malicious persons.

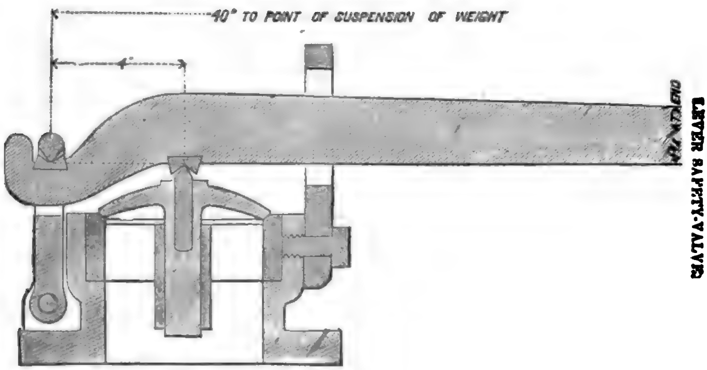


FIG. 85.—RECENT TYPE OF LEVER SAFETY-VALVE WITH KNIFE-EDGES.

A better form of lever safety-valve than that just described is that proposed by the U. S. inspectors, Fig. 85, in which the contacts of valve and fulcrum with the lever are made by knife-edges, a system found to have marked superiority over

the usual pin-construction. The valve is commonly covered by a "bonnet," and the steam flowing past the valve into the chamber so made is conducted away by an attached steam-pipe.

The proportions adopted by the Board submitting it* are as follows:

Area of Valves expressed in Square Inches.	5".	10".	15".	20".	25".	30".
Diameter of opening...	2.525	3.37	4.371	5.047	5.642	6.781
Diameter of valves....	2.76	3 77	4.58	5.28	5.86	6.375
Length of lever.......	25.	30.	35.	40.	45.	47.5
Distance of fulcrum...	2.5	3.	3.5	4.	4.5	4.75
Angle of valve's face..	45°	45°	45°	45°	45°	45°
Width of face.........	.15	.15	.12	.17	.17	.15
Length of fulcrum link.	4.5	4.5	4.5	4.5	4.5	4.5

When well proportioned and well made, these valves may be expected to keep the steam under usual conditions within

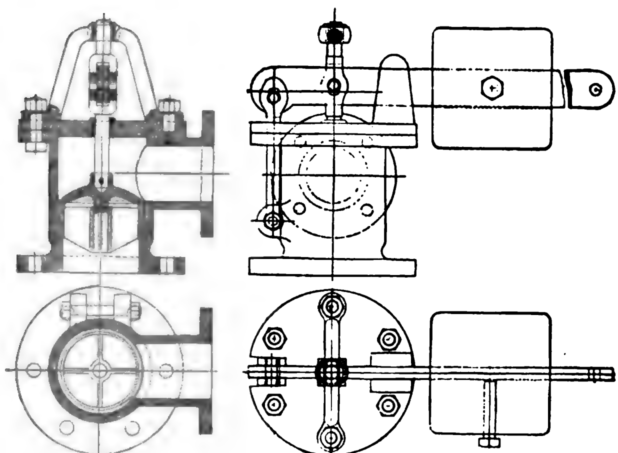


Fig. 86.—Lever Safety-valve (U. S. Board of Inspectors).

one or two per cent of its working pressure; but the smaller valves are less exact than the larger sizes.

* Report on Safety-valve Test. Washington, 1877.

The essential requirements are considered to be—

(1) Capability of discharging any excess of steam above a fixed working pressure.

(2) A minimum limit of variation of pressure within which the valve will open and close.

(3) Uniformity of action at different pressures.

(4) Reliability of action under continued use.

(5) Simplicity.

The form of valve just described meets these demands in a very satisfactory manner. The working drawings are seen in Fig. 86.

The effective area of opening, a, required to discharge a given weight of steam, w, per hour was found to be, at various usual pressures, as follows:

2 atmos., 30 pounds per square inch........	$a = w \times 0.0009$
4 atmos., 60 pounds per square inch........	$a = w \times 0.0006$
6 atmos., 90 pounds per square inch	$a = w \times 0.0003$
7 atmos., 100 pounds per square inch........	$a = w \times 0.0002$

The proportion $a = 0.005w$ is taken as giving a safe area, the factor of safety for the usual pressures being 10, and greater as the pressures increase.

In many cases the lever and weight are too cumbersome, or otherwise objectionable, and a spring is used, acting either directly on the valve or on a short lever—a common practice with both locomotive and marine boilers. Nearly all the later forms of valve are of the former of these two classes.

It is found very difficult to avoid a considerable variation of steam-pressure with the common form of valve, as it is not often practicable to secure the full lift of the valve. Owing to a peculiar action of the impinging currents of steam, it is rarely possible to obtain a rise of more than about 0.2 inch (0.5 cm.) without serious excess of pressure, especially with low steam. Many expedients have been proposed to meet this difficulty, as, for example, in the Rochow valve of Fig. 87, in which a

piston is attached below the valve, having a slight excess of area, and thus continually forcing the valve upward to the limit of its rise until the pressure is relieved.

A system now becoming very common, and giving most satisfactory results, is that known as the "reactionary" valve, of which a good example is that of Ashcroft (Fig. 88), in which the current issuing from under the valve is deflected by a curved lip or flange in such manner as to cause a pressure by its reaction that aids effectively in raising the valve. This system of construction is in very extended use.

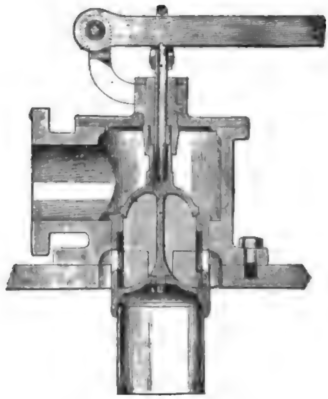


FIG. 87.—ROCHOW'S SAFETY-VALVE.

When well designed, they open promptly and widely, discharge the surplus steam quickly, and seat themselves at once, thus preventing any observable variation of working pressure.

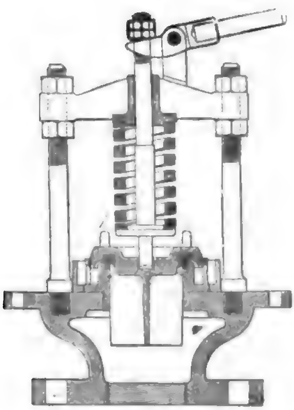


FIG. 88.—ASHCROFT'S (REACTIONARY) SPRING-LOADED SAFETY-VALVE.

In designing safety-valves care is to be taken to secure ample area of opening, freedom from liability to stick or failure to rise fully, and to see that if the spindle passes through a guide the bearing-surfaces are not liable to rust fast. It is usual to line the opening, and to cover the spindle with brass. Narrow valve-seats are advisable to secure tightness and free working, and straight steam-ways.

The mechanism of one of the most recent of the "reactionary" safety-valves is seen in Fig. 89, in which *BB* is a nickel seat, *CC*, the valve of which, *C′C′*, is the adjustable ring introduced to secure the desired reaction. *FF* is the spring and *DD* the

spindle, the one bearing against the fixed cross-bar, $G\ G$, and the other attached to it firmly. The channel, $a\ a$, turns the issuing current back into the vertical direction, and thus makes the reactionary effect a maximum.

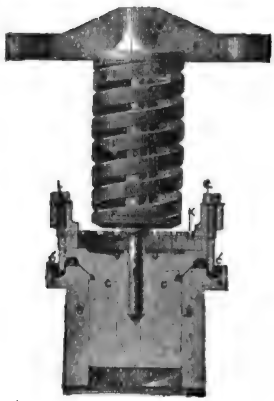


FIG. 89.—RICHARDSON'S SAFETY-VALVE.

Brass or nickel valves and seats are free from the liability to dangerous corrosion that characterizes iron.

The maximum intensity of pressure under any lever safety-valve is

$$P = \frac{wl + l'w' + w''f}{fa};$$

when a is its effective area; w, w', w'', the weight applied, that of the lever and that of valve; $l\ l'$, the lengths of lever-arm from weight to fulcrum, and of that from centre of gravity of the lever; and f the distance from fulcrum to centre of valve. The actual value of a may vary enormously in any one valve having a wide seat, accordingly as it is tight or leaking. If perfectly tight, the valve will rise when an equilibrium is reached, assuming a to be the area within the inner periphery of the seat; it will drop when the pressure has fallen so far that an equilibrium may be established, a being measured to the exterior periphery. If leaking, these two areas may have almost any apparent relation. The narrower the seat, the less these differences.

For large boilers, "multiplex" valves, consisting of a set of two or more in one casing, are often used in preference to a single large valve.

184. The Feed Apparatus for steam-boilers is not usually designed by the engineer furnishing the plans for boilers, but is purchased of makers of feed-pumps or of "injectors" as it may be needed. Where open heaters are used, in which the feed is heated before it is pumped, the injector cannot, as a rule, be used; but a large slow-moving pump, placed sufficiently low to fill with certainty at every stroke, should be employed. A

pump driven by belt and by the main engine is more economical in operation than a steam-pump. The independence of the latter, and their convenience of operation, have caused their very general introduction; and they are commonly kept at hand for emergencies, even where the "power-pump" is used. With a closed or coil heater water may be forced by the feed-pump through the heating-coils and on into the boiler. In this case, either pump or injector may be used. The latter is, in this case the more economical, as no loss occurs except of heat from the steam and water pipes, and this loss may be rendered insignificant by carefully covering them. Even the effect of friction is to give a fully compensating increase of temperature to the water.

The steam-pumps are not usually economical of steam, and often use ten times as much per unit of work done as good engines. A "duty" of ten millions is unusually large.

All feed apparatus should be of the best possible construction; should, when possible, be in duplicate, and of far greater capacity than is demanded in regular work; and should be placed where it will always be promptly and readily accessible, and kept in perfect order. Failure to act promptly and effectively in an emergency may lead to incalculable disaster. In many cases injectors are used in ordinary work, and very large steam-pumps kept in readiness for emergencies.

Heating the feed-water by means of the waste gases is always advisable if at all practicable, as well as the utilization of the heat of all exhaust-steam from engines and pumps and returns from systems of heating-pipe.

The table on page 394 gives the percentage of saving effected by heating the feed-water of a steam-boiler by means of heat otherwise wasted.

185. Minor Accessories and details, such as the kind and location of steam and water gauges, dampers, automatic controlling devices, etc., should be as carefully considered by the designer of the steam-boiler as any other parts of his work.

The Steam-gauge is selected from among the numerous styles and makes in the market, and is never designed by the engineer preparing plans of boilers. The most common form

is the Bourdon Spring Pressure-gauge (Fig. 90), of which a number of modifications are in use. The case, *A A*, encloses a coil of flattened tube, *B B*, closed at the free end and open to boiler-steam at the supported extremity. As the pressure rises and falls, a tendency to expand the tube into circular section produces greater or less effect, and the tube, as a whole, assumes a greater or a smaller radius of curvature, throwing its free end one way or the other in such manner as to measure, by the traverse of the attached pointer, the pressure at each moment, of the confined fluid. Sometimes the tube is held at its middle point, both ends being free, and their relative motion affecting the pointer. The more stable the tube and the more reliable the mechanism connecting it with the hand at the dial, the better the gauge.

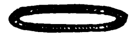
FIG. 90.—BOURDON GAUGE.

SAVING BY HEATING FEED-WATER.

(Steam at 60 lbs.)

Final Temperature, Fahr.	Initial Temperature of Water (Fahr.).												
	32°	40°	50°	60°	70°	80°	90°	100°	120°	140°	160°	180°	200°
60°	2.39	1.71	0.86	0									
80	4.09	3.43	2.59	1.74	0 88	0							
100	5.79	5.14	4.32	3.49	2.64	1.77	0.90	0					
120	7.50	6.85	6.05	5.23	4.40	3.55	2.68	1.80	0				
140	9.20	8.57	7.77	6.97	6.15	5.32	4.47	3.61	1.84	0			
160	10.90	10 28	9.50	8.72	7.91	7.09	6.26	5.42	3.67	1.87	0		
180	12.60	12.00	11.23	10.46	9.68	8.87	8.06	7.23	5 52	3.75	1 91	0	
200	14.30	13.71	13.00	12.20	11.43	10.65	9.85	9.03	7.36	5.62	3.82	1.96	0
220	16.00	15.42	14.70	14.00	13.19	12.33	11.64	10.84	9.20	7.50	5.73	3.93	1.98
240	17.79	17.13	16.42	15.69	14.96	14.20	13.43	12.65	11 05	9.37	7.64	5.90	3 97
260	19.40	18.85	18.15	17.44	16.71	15.97	15.22	14.45	11.88	11.24	9.56	7.86	5.96
280	21.10	20.56	19.87	19.18	18.47	17.75	17.01	16.26	14.72	13.02	11.46	9.73	7.94
300	22.88	22.27	21.61	20.92	20 23	19.52	18.81	18.07	16.49	14.99	13.37	11.70	9.93

Fig. 91 represents a section of the Bourdon tube. The major axis is placed vertically to the plane of the coil. Were it placed parallel to that plane, internal pressure would close up the coil instead of, as in the usual case, uncoiling it. This latter is the disposition adopted by the Author, as in Fig. 92, in a gauge devised by him for very


IG. 91.

high pressures, and especially to work steadily where exposed to heavy jar, as on locomotives.

A pair of corrugated disks, secured together at the edges, and receiving steam-pressure within, is a form of pressure-gauge spring which has been found useful, and many gauges are thus constructed. All spring gauges, unless constructed with extraordinary care, are very liable to give after a time misleading indications, and they should be occasionally tested to ascertain to what pressures the readings on the dial actually correspond.

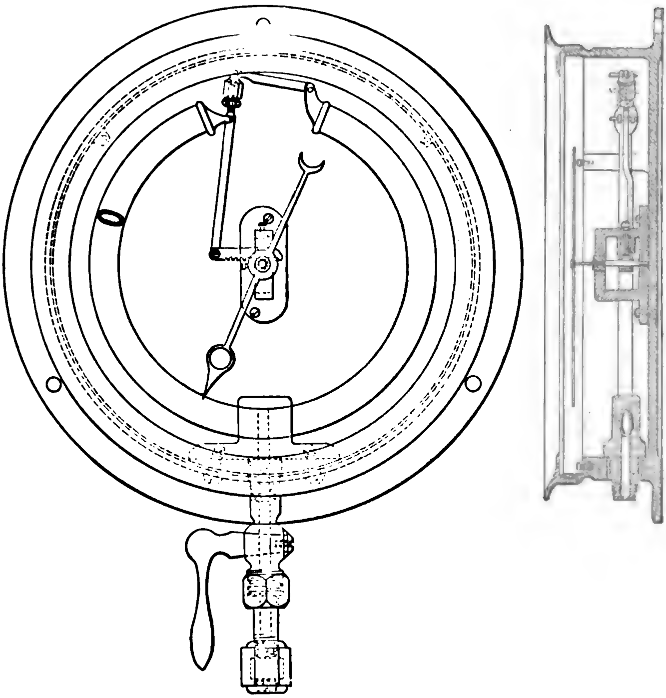


FIG. 92.—THURSTON'S HIGH-PRESSURE GAUGE.

Mercury-gauges, in which the pressure is measured by the height of a mercury column balancing it, are much safer than spring-gauges, but are too cumbersome for common use. All other steam-gauges are, however, referred to the mercury-gauge in standardizing them.

Steam-gauge connections should be so made that the instrument may not be liable to injury by heat, either externally or internally, and so that the spring shall always have a body of comparatively cold water interposed between itself and the steam. A coil or siphon-shaped bend in the gauge-pipe is generally introduced with this purpose in view: it fills up with a body of water condensed from the steam which protects the spring from injury by exposure to heat. The point of entrance of the gauge-pipe into the boiler is simply a matter of convenience, usually.

Gauge-cocks and water-gauges should be set where they will not be affected by any foaming that may occur within the boiler; they should be as far from the furnace as is convenient, or their connections should be led to a quiet part of the boiler. A foaming boiler, by deceiving the eye at the gauges, may discharge a dangerously large amount of water undetected.

The Low-water Detector and Alarm is an apparatus which is in very common use to give warning should the water-level ever fall below that considered safe. It commonly consists of a vertical tube closed at the top by a fusible plug, or by a valve actuated by a rod having a different coefficient of expansion from the tube itself. The tube communicates at the lower end with the water-space of the boiler. It ordinarily stands full of water; but should the water-level fall below its lower end, steam displaces the water in the tube, the fusible plug melts, or the valve is opened by the difference in expansion of the tube and rod, and steam at once issues, giving warning of danger. The upper end of the tube is commonly fitted with a steam-whistle, the blowing of which when the steam makes its exit insures attention.

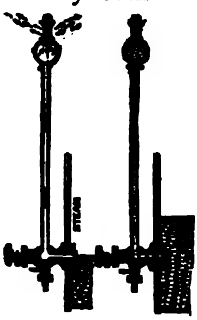


FIG. 93.—LOW-WATER ALARM.

Many forms of *grate-bars* are used in steam-boiler furnaces, some of which are provided with interlocking devices so contrived that all are so bound together that it is impossible for single bars to warp and twist out of shape to such an extent that they will be liable to burn. In other cases the bars are fitted so as to be all capable of vibration or rotation by the ac-

tion of a single handle, and thus to permit convenient cleaning of the fires. Such grates are in very common use in anthracite-burning furnaces.

Fusible plugs are inserted at convenient points in plates liable to be the first to be left dry on the falling of the water-level. A leaden rivet in an upper seam or in a rivet-hole made for the purpose at the highest part of a crown-sheet is often relied upon; but it is better to use an alloy of lower melting-point, and to make it quite large. Several small plugs are sometimes inserted in a larger plug of cast-iron properly located, the idea being to thus secure greater safety by avoiding the chance of a single one failing to serve its purpose. A large plug of fusible metal, projecting well above the crown-sheet or other plate in which it may be placed, and having a central rod of copper passing completely through it and projecting at top and bottom, is a very excellent device. When its upper end becomes exposed the copper rod melts out of its casing and falls down out of the way, exposing clean surfaces of fusible metal, which in turn melt, and the purpose of the apparatus is accomplished with certainty. In some cases alloys are so altered by long exposure to heat that they fail to melt when the emergency arises. It is advised by the best engineers that they be renewed frequently. An accumulation of sediment or scale sometimes prevents their working, or may permit their melting without causing egress of steam and water, as is usually intended. A coating of thin scale will often sustain all the pressure coming upon it over such an opening as is left by the dropping out of the plug.

The best fusible plugs consist, as a rule, of an outer shell, as in the figure, filled with a fusible metal, *C*, in the form of a plug extending through the shell from top to bottom. The shell should be of hard brass to insure strength, with a good thread where it screws into the plate, and a good hexagonal or square head, and durability sufficient to permit several fillings. The thread cut in the shell should correspond with the gas-fitters' standard. The use of such plugs is often required by law.

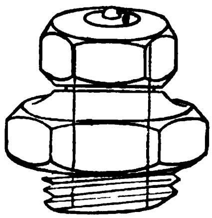


FIG. 44.—FUSIBLE PLUG.

Low temperatures can be determined by the melting-points of compositions of lead, tin, and bismuth; and the following may be used for fusible plugs:*

	Parts lead	Parts tin	Parts bismuth	Melts at ° C.	° F.
An alloy of	1	1	4	94	201
Rose's metal	5	3	8	100	202
"	2	3	5	100	202
"	1	4	5	118.9	246
"	1	..	1	141.2	257
"	1	1	..	241	466
"	..	2	1	167.7	334
"	1	3	..	167.7	334
"	..	3	1	200	392

It is customary to use such compositions in making "fusible plugs" to be inserted in the crown-sheets or tops of "connections" liable to be injured by low water, to give warning of danger, and to act as safety devices by melting when uncovered and permitting steam to issue into the furnace and flues.

All marine boilers subject to the rules of the United States Treasury Department are required to have plugs of Banca tin inserted, of not less than 0.5 diameter in the smallest part.† Cylinder boilers with flues must have one in each flue, and one in the shell not less than four feet from the forward end. Fire-box boilers must have a plug in the crown-sheet. Upright tubular boilers must have a plug in one of the tubes, two inches or more below the lower gauge-cock, or in the upper tube-sheet if so preferred by the inspector.

Where manhole covers can be "struck up" in wrought-iron, as many of them are now often made, they are much safer, as well as lighter and more convenient of manipulation. The accompanying figure illustrates such a construction as introduced some years ago. The two guards and bolts give greatly increased security as compared with the ordinary arrangement of a single guard and bolt at the middle of the cover.

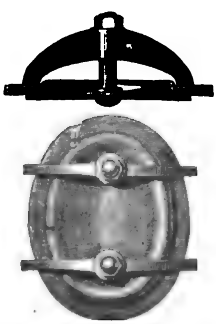


FIG. 95.—WROUGHT-IRON MANHOLE PLATE.

The M'Neil manhole cover and guard represent good recent practice, as seen in Fig. 96. The opening through the shell

* Weisbach.

† Regulations, § 22.

is strengthened by a wrought-iron "struck-up" ring, the section of which is L-shaped. The inner edge is faced to receive the faced bearing-surface of the cover, and thus makes a steam-tight joint without requiring packing.

FIG. 96.—M'NEIL MANHOLE COVER.

The "blow-off cock," which controls the discharge of water through the "blow-off" pipe, should never have a valve substituted for it, but only a good conical cock should be used. It should be of the best of brass or bronze, and of extra strength. A valve is liable to be caused to leak by the catching of dirt or of chips between it and its seat, and thus to endanger the boiler by undetected leakage. With the cock no uncertainty can exist in regard to its being open or closed, and foreign matter caught by the plug will be cut off, or the cock will be opened an instant to wash it away. A "T" placed outside the cock and so arranged that the plug can be taken out to see whether the blow-cock leaks, and if so how much, will be found an important element of security.

The "feed-valve" which controls the introduction of the feed-water into the boiler should always be a strong, well-made brass valve, of the best of metal and heavier than the customary market valves. The ordinary steam-fitter's valve and other brass-work is usually much too light, and it is often thought wise to make special patterns for boiler connections. The valve should be placed close to the boiler and the check-valve outside, and as near it as possible. Often a single valve—a "screw-check"—serves both purposes. It should be so placed that in case of the valve getting loose it may not prevent the entrance of the water into the boiler.

CHAPTER X.

CONSTRUCTION OF STEAM-BOILERS.

186. The Methods and Processes employed in the shop in the construction of steam-boilers are usually simple, and incapable of very great refinement. The boiler-maker receives a set of drawings from the designing engineer, which exhibit the general form and proportions of the boiler, and complete representations of all details.

These drawings should include front and side elevations, and plan, together with sections taken wherever necessary to exhibit the internal arrangement and structure. All dimensions should be carefully marked on each sheet, and the workmen instructed to "go by the figures," as attempts to measure by scale are apt to lead to mistakes. The thickness of each sheet should be indicated, and the location, form, and size of every opening to be made in the shop. General plans are commonly made on a scale of from $\frac{1}{16}$ to $\frac{1}{8}$ full size, according to circumstances; but detail drawings are often all made full size.

The boiler-maker often reproduces the general drawings, as well as all details, full size, on a set of large boards provided for the purpose, and, measuring all parts anew, makes sure that the originally given dimensions are all right and consistent with each other. The location of each sheet and its seams being thus determinable, the dimensions of the rectangular, or other simple form of sheet, as it is to come from the mill, are ascertained, and if not in stock, the iron or steel is ordered. Mills will usually be able to supply sheets cut very exactly to the ultimate size and shape, and thus save great expense in cutting and fitting in the shop. Every sheet should be ordered as exactly as to size as possible, and the grade and quality should be as precisely specified in the order-list thus made.

All special sheets should be exhibited by sketches as well as by figures, and in arranging their location and dimensions care is taken to bring just as few seams into the furnace and to expose riveting to the heated gases as little as possible; heavy laps, two, three, or even more sheets coming together in the joint, as is sometimes the case, are very apt to make trouble. Laps should be so planned, also, as to be easily reached for chipping and calking when necessary. The larger the sheets, generally, the better.

The order being filled, the work of construction is begun.

187. **The Apparatus, Tools, and Machinery** employed in boiler-making are of the simplest character; although the tendency is constantly observed to introduce more machine-work to the exclusion of hand-work, and to make steam-boiler construction, like iron-bridge construction, approximate more and more to the art of the machinist. The boiler-maker is coming to work more and more to gauges and standards, and the boiler is getting to be more and more a machine-made product.

The apparatus used in taking off the dimensions from the working drawings and laying them down on the sheet consists of a set of rules, scales, straight-edges, and templates. The latter are usually strips or frames, which may be laid down on the sheet, and which contain carefully spaced holes corresponding to the rivet-holes to be made, in number, size, and location; they permit the location of the rivet-holes with accuracy and dispatch.

The *tools* employed in boiler-making consist of tongs with which to handle hot rivets; riveting-hammers, especially designed for their work; chipping chisels for use in trimming the edges of plates; cape-chisels with narrow cutting edges for cutting off portions of the sheet, or making openings in it; and hammers for driving these chisels. Drift-pins—tapering iron pins which are inserted in the rivet-holes to draw them into line—are also used, sometimes endangering the construction; calking tools are used for making seams tight, and "expanders" to "set" tubes.

The *machinery* of the boiler-maker consists of heavy rolls

for giving the sheets the cylindrical form; shears for cutting them to correct outline; punches for making rivet-holes; boring-lathes or drill-presses for making the large holes in tube or flue sheets; and riveting-machines. Where large boilers, to carry high pressure, and therefore made of heavy plates, are to be built, all these tools must be very heavy and powerful. Reamers, or "rimmers," are used to enlarge holes found to be too small for their purpose. In the best-equipped establishments a planer is used to give the edges of heavy plates their bevel, and that exactness of line that is essential to neatness of appearance along the lap, as well as to secure immunity from injury by the chisel when the edge of the lap is chipped in the older way, preparatory to calking.

Various kinds of rivet-heating furnaces complete this list of apparatus of the boiler-shop. All such machinery should be very substantial and powerful, as it is always liable to be subjected to very heavy stresses.

188. Shearing, Planing, and Shaping the sheets to the prescribed size and form are operations preliminary to the fitting together and riveting up of the work.

Shearing is performed by the "shears" or shearing-machine, which consists of a pair of strong jaws, of which the one is fixed, the other movable, and actuated by a powerful toggle-joint or by an eccentric. The cutting edges are usually straight, but set at a slight inclination the one with the other, in such manner that the cut begins at one end of the blade and runs across to the other, thus enormously reducing the force required to effect it. This operation is rapid and inexpensive, but is liable to injure the metal near the cut if it is hard, and usually leaves so rough an edge that it is advisable to give a better finish by means of the planer. Sharply curved and irregular outlines cannot be given by the shears or the planer, and are formed by the chisel. Occasionally, the rough work is done by drilling a series of holes along the line to be cut, and dressing out to the line with the chisel.

189. Flanging sheets which are to receive the ends of flues, or are to be used as heads and riveted to the shell, is performed at open fires, by means of which an even heat is ob-

tained over the whole area to be worked, and the flange is then made by hammering the edge to be turned, over an anvil or properly shaped "former." In some cases, when considerable numbers of circular or other simple forms are to be flanged, flanging-machines are used, in which the whole flange is formed at one operation, the disk being forced by hydraulic pressure into a die which turns up the flange all around. In some cases dome-tops, manhole-rings, manhole-plates, and other parts are similarly "struck up."

Punching and drilling are performed by machinery usually, and for the latter process the gang-drill is often found an economical machine: it consists of a collection of drills so set as to be driven together, and so to make a number of holes at once. Punching is generally practised with very soft steels, and with all iron; but drilling is always preferable where steel is employed of appreciably greater hardness than good iron, and is probably safest with hard irons.

A good rule in working steel plate is to punch the holes $\frac{3}{16}$ inch (0.476 cm.) smaller than the size of rivet, and then to enlarge the hole to full size by either counterboring or reaming. The sharp edge, or fin, if any, around the hole should finally be trimmed so as to make a slightly rounded fillet under the head of the rivet, and thus reduce the risk of fracture at that point.

For these operations the holes have been previously marked off by the template, and the art of successfully doing the work is mainly that of securing exact location of the punch or drill at starting. A table, carrying the plate and moving automatically the correct distance to give the desired spacing at each operation, is often adopted, and with advantage. When punching, the sheet should be so placed that the side at which the punch enters shall be that next the adjacent sheet when riveted up, thus producing a hole for the rivet largest on the outside, next the heads, and smallest at the middle.

190. Bending Plates to the required curvature is often the first process, though frequently performed after the operations just described are completed. The bending rolls are so set as to produce a moderate degree of curvature at the first

passage of the plate, and repeatedly adjusting the rolls and successive passes of the sheet finally give the full curvature desired. Where the shape to be secured is the frustum of a cone, one end of the sheet is more closely pressed in the rolls than the other, and a sharper curvature given it. The use of a template determines when the plate has the right curvature.

191. **Riveting** is done partly on detached portions of the boiler, as in making flues and fireboxes, and partly in assembling such parts and building up the complete structure. As a rule, all parts which can be easily handled are completed separately, and later joined to adjacent parts in the final work of putting them all together. Each member being comparatively light and small, the work can be done on it, detached, much more conveniently, rapidly, and cheaply than when it is attempted to construct it as an attached portion of the larger mass.

Before riveting up, each seam is examined to see that the two halves of the lap are precisely matched, the edges parallel and well adjusted, and opposite rivet-holes all exactly located and fair with each other. Should any fault appear it is corrected before riveting is begun. While making this trial of parts and doing this fitting, and while making this examination, the seam is temporarily held by bolts which should nearly fit the holes intended for the rivets. Should a pair of rivet-holes be unfair, the bolt will not enter, and one or both the holes must be dressed over with a reamer until the rivet can enter. The drift-pin is used to bring companion sets of holes opposite, when in doing this the plate requires to be slightly sprung; but it ought never to be employed to enlarge the holes or to force them fair by visibly distorting the sheet or the metal about the hole. When this process seems necessary, and when enlargement by chipping produces a seriously misshapen hole, the faulty sheet, or pair of sheets, should both be in fault, should be condemned, and better prepared sheets substituted.

When the seam is found to be right, the two edges are bolted firmly in position, with the laps in perfect contact, and riveting proceeded with. Every rivet should be of the length

and size required by specification, and of the best material. In heating, the shank is given a good forging temperature, the head left barely red, and the point safely inside the burning heat. A few blows on the laps, with the rivet in place, determine whether metallic contact exists, and the rivet is then rapidly headed up and shaped. Quick work means easy and good work, as the riveting is then finished before the rivet is hardened by cooling. Riveting-hammers are comparatively light; but the rivet is held up to its place by heavy hammers,

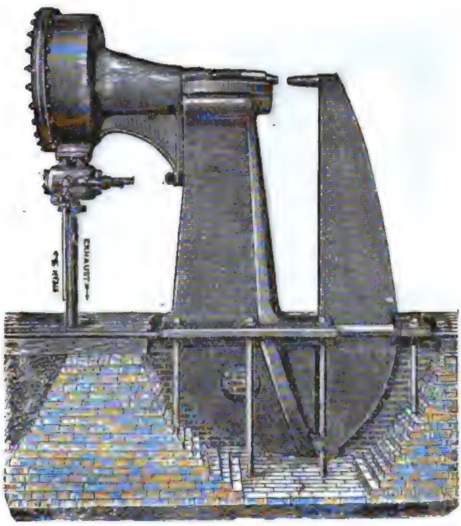


FIG. 97.—STEAM RIVETING-MACHINE.

weighing from ten to sometimes thirty or forty pounds (4.5 to 14 or 18 kgs.), and capable by their inertia of resisting the heaviest blows struck during the operation. Two or three hundred blows are required for each rivet in ordinary boiler-work. Very heavy rivets are headed up with a "button-set," a forming tool which is cup-shaped at one end, where it rests on the point of the rivet, while blows of a sledge-hammer on its other end drive it down and so give the head a hemispherical shape. This form of head is stronger than the cone-shape usually given in hand-riveting.

Machine-riveting, either by steam, compressed air, or hydraulic machines, is, if well done, preferred to any hand-riveting; although on work which is not too heavy the latter is thoroughly capable of giving satisfaction. In machine-riveting the machine should be amply powerful; the die should be carefully brought in line with the rivet; the laps should be very closely secured together, and the pressure fully up to the working standard. A machine which will clamp and hold the lap while the rivet is driven is to be preferred.

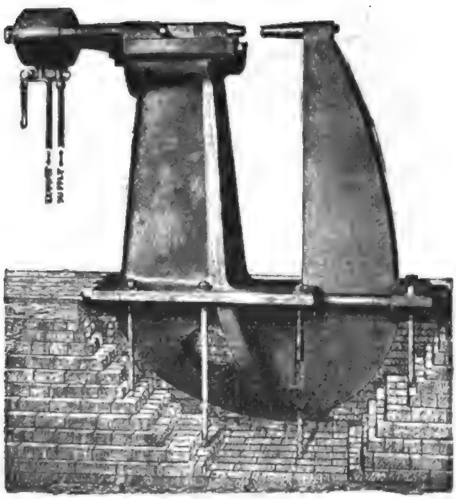


Fig. 98.—Hydraulic Riveter.

Well-constructed steam-riveters of angular size do their work by pressure, not by impact or blow. The boiler-pressure should be varied to suit the size of the rivets being driven, and maintained at a uniform pressure during the entire work. A good steam-riveter should drive ordinary sizes of rivets ten times as rapidly as a single gang of riveters working by hand, notwithstanding the time and labor required in the handling and adjustment of the boiler, the rivet, and the machine. The lighter machines are compelled to strike a blow: this gives less satisfactory and far less reliable work than when the machine has

sufficient power to head up the rivet by steady pressure. In working this machine the rivets are inserted from the outside of the boiler, instead of, as in hand-riveting, from the inside. The boiler, suspended in slings attached to a crane, is drawn up to the riveting-hammer, and the pressure heads up the rivet in a moment, and the steam-pressure is retained until the rivet is cool. The charge of steam used in riveting is sometimes utilized in its expansion to draw back the ram.

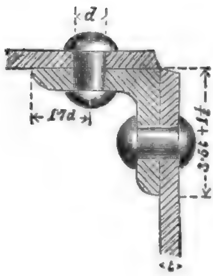


FIG. 99.

FIG. 100.

To drive rivets by hand, two strikers and one helper are needed in the gang, besides the boy who heats and passes the rivets; to drive each $\frac{5}{8}$-inch rivet an average of 250 blows of the hammer is needed, and the work is but imperfectly done. With a steam riveting-machine, two men handle the boiler and one man works the machine.

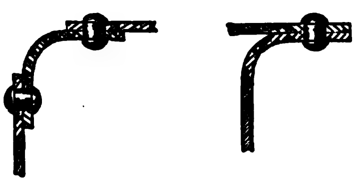


FIG. 101.

Where the plates of which portions of a boiler are composed meet at right angles, the connection may be made by either of the methods exhibited in the illustrations above: as by angle-iron (Fig. 99); by a T-iron, when stiffness is desirable in the transverse plane (Fig. 100); or by flanging (Fig. 101).

In order to exhibit the relative advantages of machine and hand riveting, we have in Fig. 102 an illustration of two plates

riveted together, the holes of which were purposely made so as not to match perfectly. Rivet *a* was put in by the steam-riveter, and *b* by hand. The machine-rivet fills the hole completely, while the hand-rivet is very imperfect.

The hand-rivets fill up the holes immediately under the head formed by the hammer; but sufficient pressure could not be given to the metal by hand to insure equally good work.

The hydraulic riveting-machine compresses without a blow, and with a uniform pressure, variable at will; each rivet is

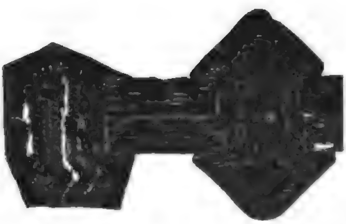


FIG. 102.—HAND AND MACHINE RIVETING.

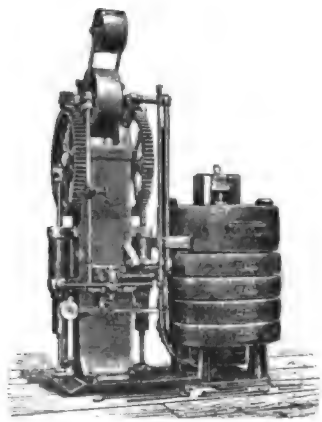


FIG. 103.—ACCUMULATOR AND PUMP.

driven with a single movement, under complete control. The pressure upon the rivet after it is driven is maintained, or the die is retracted, as may be desired. This machine consists of a riveting-die attached to a piston in the compressing cylinder; this cylinder communicates with an accumulator through a valve moved by the operator. The work is performed without a blow; the pressure is always uniform, and can be adjusted by the weights applied to the accumulator; it may be maintained as long as desired, or the riveting-die can be retracted as soon as the rivet is finished. The succeeding diagrams illustrate this system.*

* Supplied through the courtesy of Messrs. Sellers & Co.

Cold-riveting can be successfully adopted on light work when the best material can be obtained in the rivets, and is preferred where choice is allowed on account of the greater certainty in regard to quality of rivet and the freedom from risk of injury by heat.

Steel rivets must be worked more rapidly than iron.

The accumulator is an essential part of the system: in it water is kept under pressure by means of a pump, or otherwise. The chamber of the accumulator is closed at one end, and to the other end is fitted a stuffing-box through which a weighted

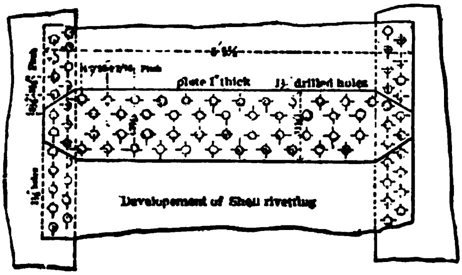


FIG. 104.—HEAVY LAP.

plunger rises or falls as the quantity of water in the chamber increases or diminishes. By varying the load upon the plunger, the pressure upon the water in the accumulator-cylinder is adjusted. The water under pressure in the accumulator is there stored ready for use, and is conveyed through suitable pipes to the compressing cylinder of the riveting-machine, so that when the valve is opened the water flows into the cylinder, forcing the riveting-dies upon the rivet, and finishing the work with such force as the accumulator has been gauged to produce. The very high pressure at which hydraulic machines are operated, as compared with steam-riveters, makes the cylinder smaller and the machines less cumbersome. The hydraulic riveting-machine can be used wherever power by belt is obtainable, and the pumps and accumulator may be placed at any point most convenient for the application of the power. In bridge- and ship-building the portable hydraulic riveter is commonly employed.

The adjustment of laps and of courses, where the metal is thick and construction intricate, often demands much ingenuity on the part of either the designer or the builder of the boiler. Fig. 104 illustrates the usual arrangement in the shell of marine boilers of the Scotch type, where, as is customary, butt joints are employed with double riveting.

The following sketches illustrate some of the best forms of joint in standard construction, beginning with the single-riveted joint of everyday use, and followed by various forms of double and triple riveting.

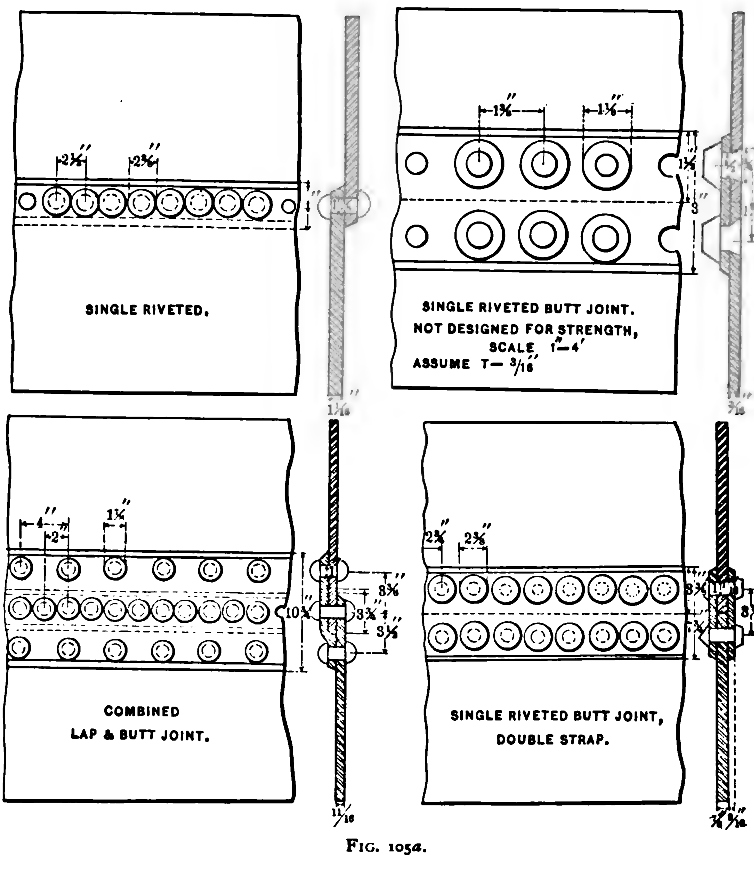


FIG. 105*a*.

These joints are all proportioned as for steel, and a strength is assumed of 5000 pounds per running inch, the factor of safety being taken as 8, or for 8000 pounds if the factor be dropped to 5.

The second of the group shows the junction of four overlapping plates; and the third the method of arranging the covering-strips or "cover-plates."

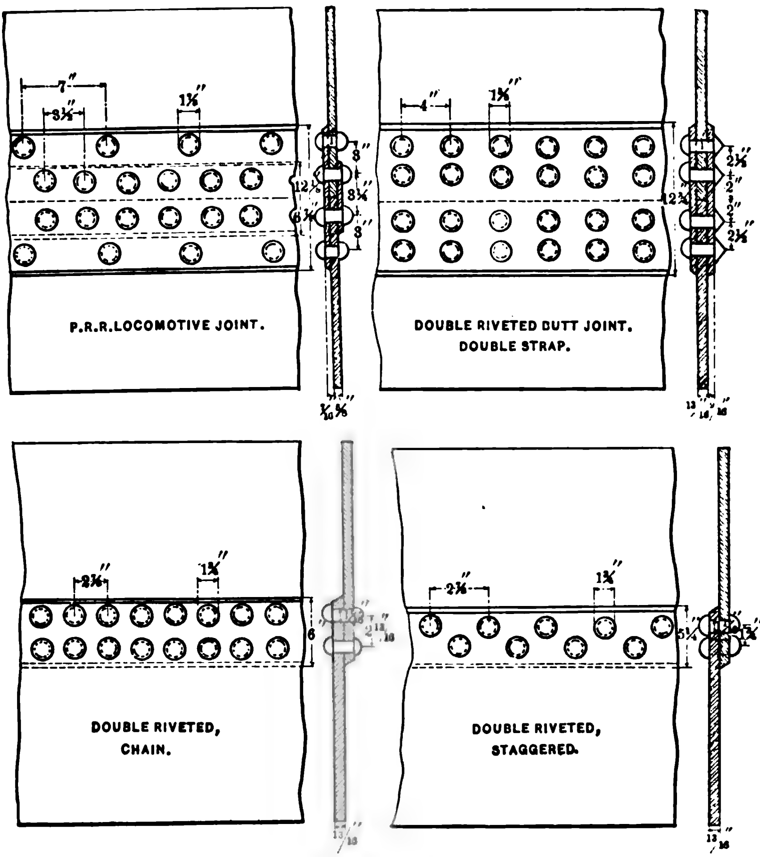


FIG. 105*b*.

Where, as should always be the case, steel plates are drilled, or are punched and the holes sufficiently enlarged by counter-boring or reaming and the plates finally well annealed, no al-

lowance need be made for loss of strength in the metal between the plates.

The best makers of boilers endeavor to reduce the number of seams to a minimum, as well as to make those retained of uniform and ample strength. Double-riveted longitudinal seams are becoming constantly more common, and in some cases welding is resorted to with great success. The latter plan permits the securing of perfectly cylindrical courses or rings of plates. It seems not improbable that welding may ultimately become the usual method of making all joints. The

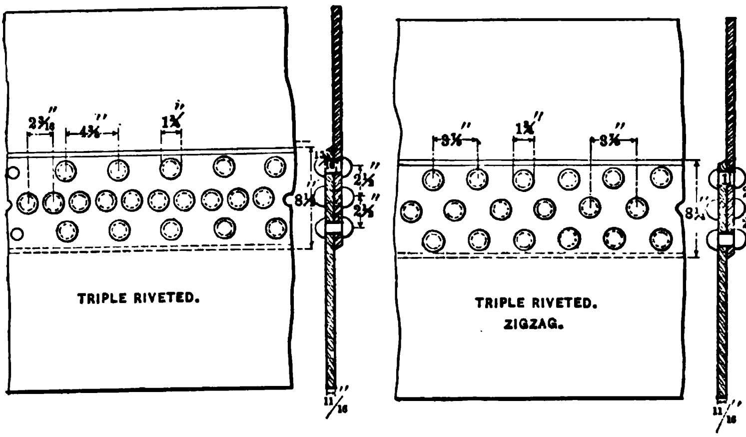


FIG. 105*c*.

lap-joints are disappearing in good designs, and the butt-joints, single and double riveted or other, are taking their place. In these cases the cover-plates, or covering strips, or straps, as they are variously called, should be cut from plate, and in such manner that the grain shall run parallel with the direction of stress.

Welding, if it can be safely relied upon, offers so many advantages over riveting, that there can be no question that it will in time supplant entirely the older method of uniting the parts of boilers. It has been the practice of a few makers to employ this system for many years, and the use of welded seams is slowly but steadily increasing. A good weld gives more nearly the full

strength of the iron than can any arrangement of rivets, and enables all risks arising from defects in workmanship peculiar to riveting, such as drifting or careless chipping and calking, and such as cold-hammering, to be avoided. It permits dispensing with calking entirely, and consequently the avoidance of the grooving or furrowing which so often proves dangerous. It is also possible to reroll the course or ring of welded plates, and thus to secure greater accuracy of dimension and perfection of form than could be obtained with riveted work.

Welding is less likely to prove unreliable in flues than in shells of boilers; as the steam-pressure there tends to force the parts together, rather than to separate them, as in the latter case. Great experience is in any case demanded, as well as great care and skill, in making long lines of weld, such as are required in this work. It is stated by Mr. Adamson, who has been one of the most successful makers using the process, that the metal must be of the best possible quality, and that steel containing enough carbon and other elements, to perceptibly harden it cannot be safely employed.

192. **Flues and Tubes** are set after the parts of the boiler are assembled, or in the construction of the tube-boxes and "connections." The flue is commonly riveted into the flanged opening cut into the two flue-sheets to receive it; the tube is "expanded" into the tube-sheet by means of a "tube-expander," of which there are many kinds; which tool forces out the tube into metallic and firm contact with the hole bored to receive it, and at the same time expands it a trifle on each side the sheet, and thus tightens its hold and gives it the effect of a stay, while still further insuring against leakage. Care must be taken to avoid too great expansion, as the tube-sheet is sometimes strained and weakened by excessive stretching, and the tube itself is sometimes split. Properly set and expanded, a tube makes an exceedingly effective stay. A locomotive tube should safely carry 3000 pounds (1360 kgs.) and a marine boiler tube, of double the diameter, 5000 pounds, (2268 kgs.), or the full boiler-pressure ordinarily carried. For very high pressures, as now often attained with three and four cylinder "compound" engines, stay-tubes are introduced at in-

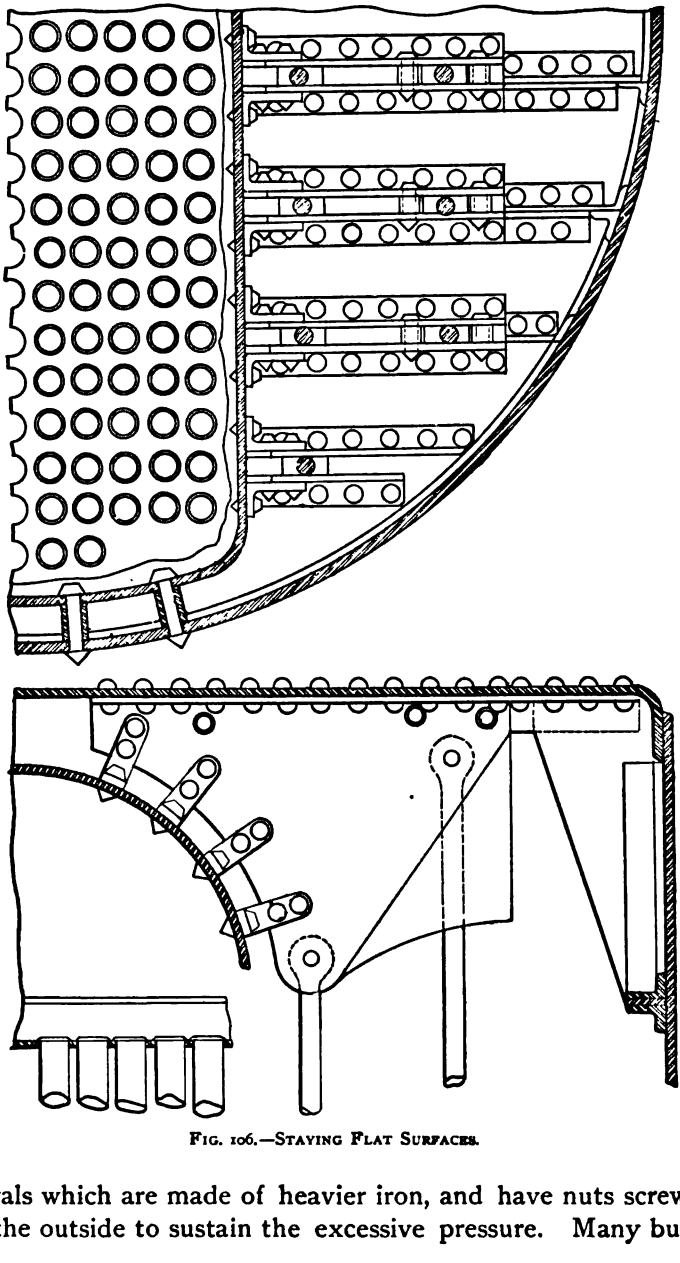


FIG. 106.—STAYING FLAT SURFACES.

tervals which are made of heavier iron, and have nuts screwed on the outside to sustain the excessive pressure. Many build-

ers prefer not to bead over the ends of the tubes, fearing that the operation may loosen them and cause leakage. The ends of the tubes are annealed before expanding them.

In laying out the flue or tube sheets, the centres are located by reference to the drawings, and the outline of the hole is laid out by the dividers. For flue-sheets, a row of small holes is drilled around the circle, marking the opening to be made; the centre part is cut out, the opening trimmed and flanged, and the sheet is then ready to receive the flue. Tube-sheets are similarly laid off, a small hole drilled at each centre, and the hole then "counterbored" to the required size and the edges of the enlarged holes smoothly rounded to prevent cutting the tubes when expanded in place.

Ferrules are often driven into the tube-ends, partly to give greater tightness, partly often to reduce the draught-area when, as sometimes occurs, it is too great.

Staying is variously practised, and marine-boilers especially exhibit a great variety of methods. Fig. 106 illustrates a somewhat peculiar method of staying adopted in the boilers of the U. S. S. Nipsic. A set of gusset-plates is riveted to the shell, and the connection is stayed to them by means of lugs riveted to both. The long stay-rods running lengthwise of the boiler are connected to these gusset-plates. Other gusset-plates stiffen the junction of the adjacent parts of the shell above the connection. The water-spaces are stayed by riveted stay-bolts in the usual manner.

Fig. 107 illustrates the staying of the heads of the boilers of the U. S. S. Monadnock.

Fig. 108 exhibits the method of staying adopted in the boilers of the U. S. S. Miantonomoh, which differs from the more common practice in the manner of fastening the heads of the stay-rods. The eyes to which the rods are attached at the end are made fast to the shell by means of bolts passing through the plates and held by nuts on the outside.

The usual method of securing the stay-rods and "crow-feet" in marine-boiler construction is seen in Fig. 109, as practised in the boilers of the U. S. S. Terror.* A set of I-irons is

* Shock on Boilers.

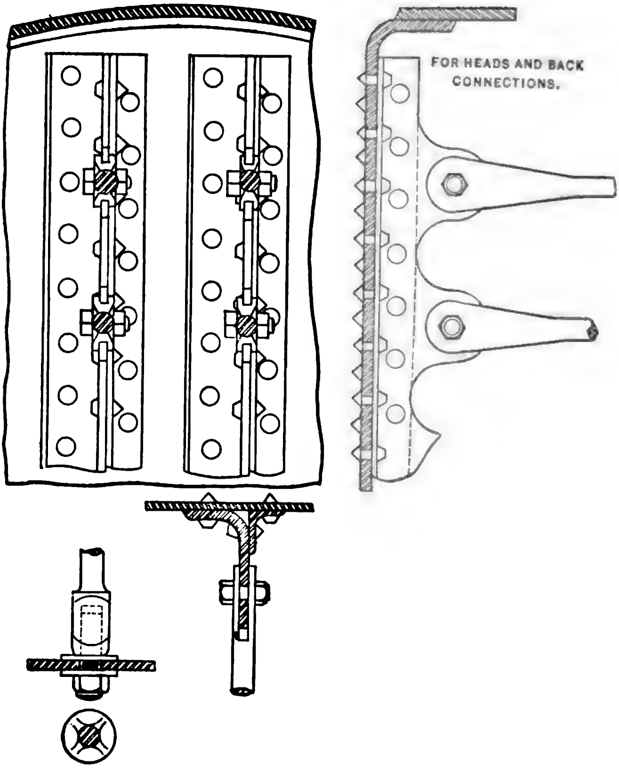


FIG. 107.—STAYING FLAT SURFACES.

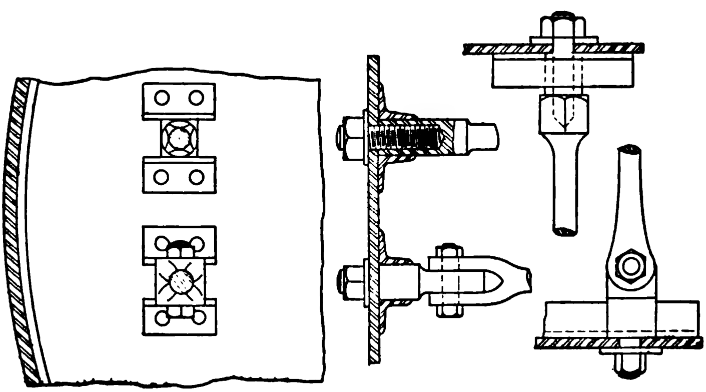


FIG. 108.—STAYING FLAT SURFACES.

riveted on the inside of the shell which gives an anchorage for the crow-feet to which the stay-rods lead, the connections being made by bolts in shear.

Fig. 110 represents the method of staying adopted in the boilers of the S.S. Lord of the Isles to secure the heads.

193. Chipping and Calking seams after they are riveted up is a process which is relied upon to insure against leakage. The workman, with hammer and chisel chips the edge of the lap smoothly from end to end—sometimes only on the outside, but often, if accessible, on the inside, and thus obtaining a smooth edge; then drives a blunt "calking-tool" against it, and thus expands the metal against the opposite plate, and securing metallic contact closes every leak.

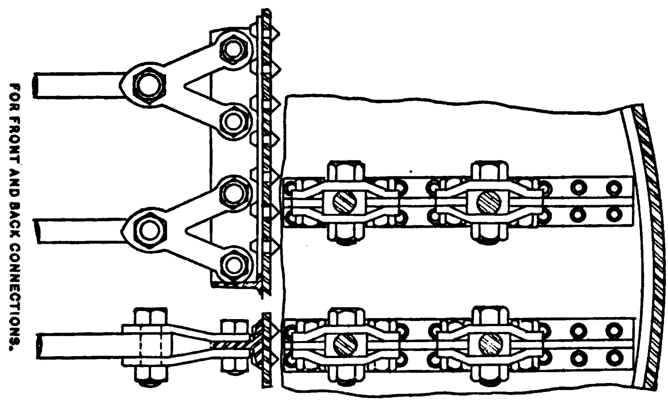


FIG. 109.—STAYING FLAT SURFACES.

The process of chipping is a dangerous one, and the score produced by the chisel as its corner marks the under sheet has been often known to lead to the formation of a groove or a crack, and later to explosion. Planing the edge before final assembling and riveting up is much to be preferred. The use of the calking-tool has sometimes resulted in similar injury; and split-calking, which consists in driving the edge of a chisel into the edge of the sheet and thus splitting it slightly and expanding the lower part against the adjacent sheet, is advised as a safer plan. The Connery system, regarded by many as very much better than either of the preceding, is similar to the last;

but a round-nosed tool is employed which makes a smooth, semi-cylindrical groove instead of a sharp crack. The expanding effect is also felt further back under the lap, the seam is thus tighter and more permanently so, and the use of the tool is not liable to injure the lower sheet.

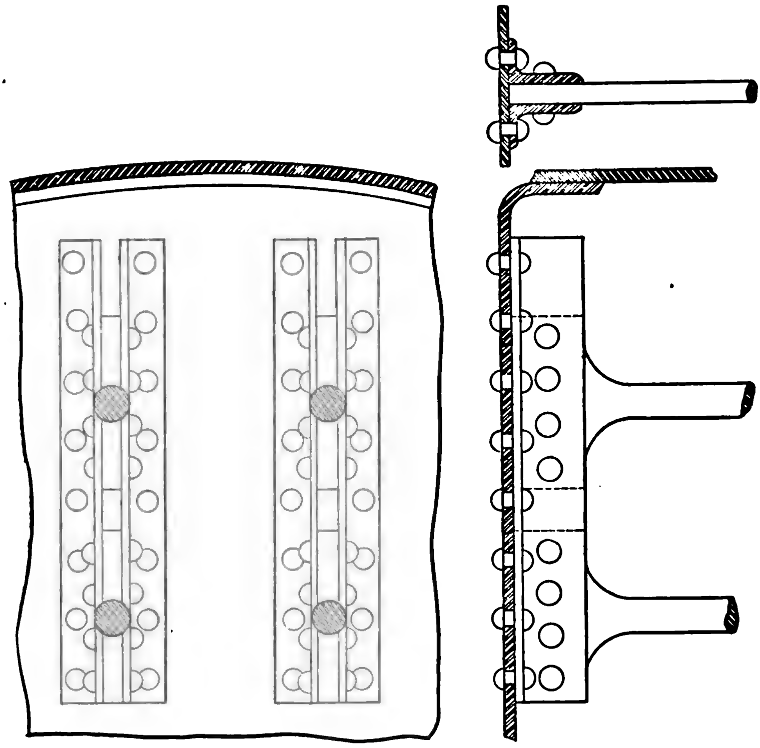


FIG. 110.—STAYING FLAT SURFACES.

In European practice, even where the builders have not gone so far as to adopt the system of calking with a round-nosed tool, they have very generally substituted for the old and dangerous form of calking-tool a wider-edged tool called the fullering-tool, and the specifications usually prescribe fullered seams as well as planed edges. No calking-tool should ever be permitted to be used which has a sharp edge or corner that may by careless handling be made to cut, or even mark, the sheet at the edge of the lap.

Butts are calked with a tool which makes a depression on each side the line of junction, expanding the two sides into contact and making that line tight. It is customary with some makers to calk around the heads of rivets, and when found leaking this process is resorted to as a remedy. Calking should not be done while the boiler is under pressure, and should be very carefully done at all times.

The "concave" calking, so-called, is exhibited in the accompanying figure, which shows the difference in the effect of the new and old methods upon the sheet. The plate is shown, as bent after the operation, to determine the extent to which injury of the plate may have been incurred. On the left is seen the action of the concave system, the effect of the tool being somewhat more marked than is customary, but perfectly representing samples in possession of the Author. On bending

FIG. 111.—CONCAVE AND COMMON CALKING.

down the sheet, as shown, it is seen to be quite sound, and entirely unaffected by the action of the tool. On the other hand, the ordinary tool, as commonly used and as illustrated on the right in the same engraving, is almost invariably found to produce a slight indentation of the sheet along the edge of the lap, and then to cause a tendency to crack when the sheet is flexed by the changing temperatures of the boiler and accompanying strains. By this method either the edge of the tool or the edge of the lap is liable to produce a dangerous groove, at once or after corrosion has progressed somewhat. The more rational system gives a broad band of metallic contact between the two sheets, and makes the joint tight without injury to the structure.*

In using the "round-nosed" calking tool, the following directions should be observed:

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* Journal Franklin Institute, 1874.

Chip or plane the plates to an angle of about 110°, seeing that the seams are perfectly close inside and outside. Apply the tool in the usual manner, forming a channel, and always keeping the burr between the tool and plate, and calk until found solid, smooth, and brought to a feathered edge, free from pin-holes. Do not cut off the burr, as it may injure the under plate. Upon testing, if pin-holes are found, apply the same tool as before, until made perfectly tight. The convex tool should taper about two inches from the point, which is about half an inch wide, otherwise perfectly straight, save when unavoidable, and ground to a radius that will finish the concave channel to about one half the bevelled edge; if too wide it will thicken the edge; if too small it will wedge it off.

194. **Assembling** is the process of fitting, and finally riveting permanently together, all the details and members, which, separately constructed, are finally brought together to make the complete structure. The shell, the tubes and their tube-sheets, with the front and back connections and the steam-drum, are the several principal parts thus dealt with. The shell is first set in position and riveted up; the flues or tubes and connections are next finished, placed in their proper position within the shell, and riveted into place; the drum or dome is attached; and, finally, all minor details are added, and the boiler is ready for examination, test, and finally for calking and "finishing."

195. **Inspection** of the work should take place, not only when the boiler is reported completed, but should be kept up constantly throughout the whole period of construction. Where extensive contracts are filled, it is usual for the purchaser to have a skilled inspector constantly employed to see that the material introduced is in accordance with the contract; that the construction is precisely what is called for by the drawings and specification, the work well done, and the whole properly put together.

A special inspection is usually provided for, to take place at completion and before acceptance. At this time the inspector very carefully and minutely examines the boiler inside and out, overhauling the braces and stays, their connections with the shell and other parts, and their welds and fitted parts; he observes the character of the riveting, the method of attach-

ment of the various accessory members; the valves, cocks, and gauges, if attached; and every detail, great or small, comparing all with the specifications and drawings, and noting any defect, either in general construction or in workmanship. Any defective material or bad work is condemned, and must be replaced by good material and with better workmanship. The final inspection proving satisfactory, the boiler is tested. The work of inspection is often, perhaps in good practice almost invariably, provided for by specifications attached to the contract and forming part of it. Such specifications direct every step

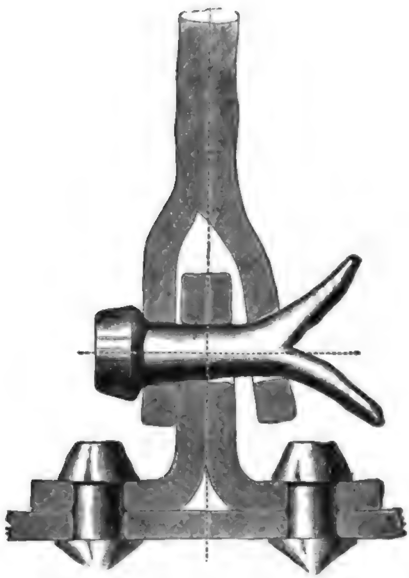

FIG. 112.—DEFECTIVE PINNING.

from the preliminary visual examination of the material when received, or even sometimes the watching of its manufacture in the mill, through all intermediate tests of iron, steel, or finished parts, to the final examination and pressure-tests of the completed structure, and the method of recording measurements and tabulating them and of making the reports for which they furnish the texts.

The defects sometimes revealed by inspection are flaws in the iron in parts not readily seen; inferior iron in concealed portions of the boiler; cracked flanges or laps, either in lines

from rivet-hole to rivet-hole, or from the rivet to the edge of the plate; "unfair" or "half-blind" rivet-holes; weak and narrow

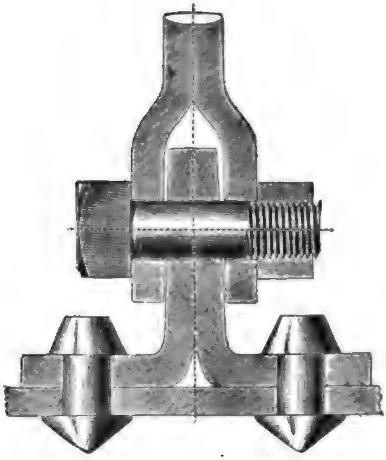

FIG. 113.—CORRECT CONSTRUCTION.

laps; injury by calking or by chipping; laps not well closed; narrow water-spaces; injured tube-ends; loose and badly set and fitted braces and pins; omitted stays or braces; and minor defects.

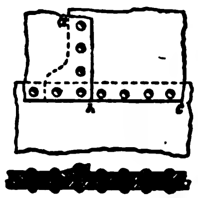

FIG. 114.

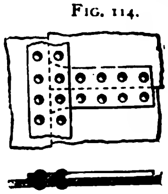

FIG. 115.

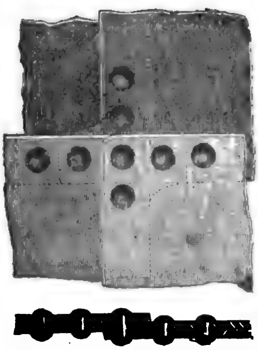

FIG. 116.

To ascertain whether a sheet is of the right thickness, a small hole is sometimes drilled at the suspected point. The connecting of stays should be condemned if not as in Fig. 113; they are sometimes found as dangerous as the case illustrated in Fig. 112.

The junctions of plates meeting at the intersections of seams are given the shape seen in the accompanying figures, the first showing the junction of three sheets as where the longitudinal

and transverse seams meet in overlapping courses, the middle plate being thinned to give proper bearing.

196. **Testing Boilers,** when under inspection, at the time of acceptance, usually consists simply in filling them with cold water, applying a pump, and subjecting them to a pressure exceeding that at which they are to be used. It is better to warm the water to the boiling-point nearly, as the pressure then affects a boiler more nearly as under the conditions of actual use. The temperature should not exceed the boiling-point under atmospheric pressure, as an explosion or serious rupture might follow the revelation of a defect—a result which has actually occurred in more than one instance.

The pressure should be applied very carefully and steadily, and the steam-gauge watched to detect any sudden drop of pressure which would indicate yielding. The breaking of a brace is usually revealed by a sharp report. Gradual yielding is shown by a cessation of rise of pressure, or by its falling off. Leaks show themselves whenever seams have not been made tight, and are traced out by trickling drops or running streams, and are marked with chalk or a pencil for later calking. The connection of large steam-drums or domes with the shell are apt to show weakness, and should be carefully watched as pressure rises.

The pressure is finally relieved, the boiler emptied, all leaks stopped, and the test repeated if the result is not satisfactory. In filling boilers, care should be taken to run them full of water to the very top of the safety-valve case; as any confined air might make trouble.

Testing a boiler by filling it to the safety-valve with cold water and then starting a fire is advised by some writers as a very safe method; since the pressure can be run up, if the boiler is tight, to any desired point without exceeding the boiling-point under atmospheric pressure, and thus without danger in case of a weak spot revealing itself. The temperature should not be allowed to go higher than that limit, as a boiler filled with water at the temperature due a high steam-pressure is more dangerous than when under steam at the same pressure.

197. **Sectional Boilers** are constructed, so far as composed

of riveted work, precisely as are other boilers; but they are usually constructed mainly of nests of tubes, connected by cast or forged "headers," which are fitted together with machined or "faced" joints, and held by bolts. Each header has its tube-end either screwed or expanded into it, or in some cases simply slipped into place and made tight by packing. In these boilers the special precautions to be observed are to see that the joints are well made and permanently tight. The facing off should be so perfectly done that a thin coat of red-lead paint, at most, should be all that is necessary to make the joints tight against any steam-pressure. The best makers do not even use this precaution.

198. Transportation and Delivery are effected usually by the maker. Small boilers are simply loaded on strong wagons and carted off to the place at which they are to be delivered. Heavier boilers often require specially constructed vehicles, and the very cumbersome structures often seen where marine flue-boilers are employed are sometimes transported on skids and rolls as houses are moved.

In hoisting boilers to place them on the vehicles on which they are to be transported, or in setting them, great care is required to see that they are so handled as to introduce no risk of straining them. The best method of slinging them should be carefully studied; the tackles used should be of more than ample strength, and no risk of sudden fall or change of position should be taken.

CHAPTER XI.

SPECIFICATIONS AND CONTRACTS.

199. The Purpose of Specification and Contract is to present a perfectly definite and exact statement of the character and extent of the work to be done: the forms and proportions of details, the time to be allowed in construction, and the amount and method of payments to be made by the purchaser.

These documents are always prepared when any work of importance is to be done, and are signed by the two contracting parties, or by authorized representatives or agents. They consist of a formal contract, or statement of obligation, with specifications describing all work to be done, and, where the case permits, of a set of drawings of everything to be made, in full and in detail; which drawings form a part of the contract as well as of the specification.

200. The Contract is an agreement in writing by which the one party to the bargain agrees to do a certain exactly specified work, and the other to make compensation in a certain stated manner, and often with provision of penalties for failure to fulfil the terms of the contract. This agreement represents as exactly and clearly as possible the mutual understanding between the contracting parties in regard to all business relations involved in the performance of the work to be done. Everything needed to make the understanding definite is embodied in the contract. Advertisements, proposals, and preliminary agreements are often taken as parts of the contract, as well as drawings and specifications. These papers are made out in duplicate, and are signed by both sides, each retaining a copy. Where many interests are involved, representatives of each should sign and each should retain a copy.

The essential conditions of a legal contract are that it shall be definite as to the obligations of both sides; that the com-

pensation be stated and valid; that mutual consent be secured by voluntary act; and that the parties in interest shall all sign of their own free will, and with a full understanding of the obligation assumed. The mentally or legally incompetent cannot take part in any contract while such disability exists. The agreement is interpreted by its own reading, and the private intentions of the makers have no weight, nor have their mental reservations. The document is its own commentary and proof. Interpretations of terms are settled by the customary and habitual use of the term, and if technical, the word or phrase must be taken as having the meaning usual in the business. Obscurity of wording may vitiate the agreement.

The duty of each party to the contract is to be separately defined and described. The contractor is bound to perform a specified work in a satisfactory manner, to complete it in a specified time, and to accept a stated compensation, made in a manner and as to time clearly prescribed. The other party to the bargain is bound to make full compensation to the extent and in a manner stated, to aid in all proper ways in the carrying of the agreement into effect, and to at all times meet the contractor in a fair and helpful spirit. The work is the contractor's until paid for as prescribed by contract; when so paid for, it becomes the property of the employer, who only then carries any risks on it, unless otherwise provided in the agreement.

Penalties incurred by non-fulfilment of the terms of the contract are of the nature of a standing debt, and may be similarly held and collected. Non-fulfilment of an agreement by the one side does not necessarily give freedom from obligation to the other, except where such failure on the one side may interfere positively with the operations of the other. In statements of time, a day ends at midnight. No time being stated, the work must be done within what may be decided to be a "reasonable" period.

Action at law must usually be entered against one guilty of breach of contract within six years; but the Statute of Limitations varies in different states. A guaranty and bond is sometimes exacted to insure the completion of the contract; but this is usual only in public work.

201. The Form of Specification is such that every descriptive portion of the contract may be embodied in it, in a systematic manner, in proper relative order, and in thoroughly definite shape. The character of materials to be employed; the method of working them; their final form; the quality of the workmanship; all instructions that may be needed in regard to the performance of the work—are given in the specifications. Since this document is that on which the intending contractor makes his offer, it must be absolutely complete, and as concise as possible. No detail should be omitted, and nothing should be left to be assumed or disputed.

202. Specifications for Steam-boilers should not only comply with all the legal conditions of a sound contract, but should represent the best known practice of the time. They should be prepared by the designing engineer, and, with all drawings, advertisements, blank proposals, agreements, and intended form of contract, laid before the employer for careful discussion and final approval before any step is taken in the receiving of bids or the acceptance of proposals. They should include a full description of the boiler to be built, with complete drawings, general and in detail; statements of the kind, make, and quality of the iron or steel to be used, the character of the workmanship to be demanded, the kind of tests to be applied, and every condition having a bearing on the subject.

203. Sample Specifications are as follows, illustrating standard practice in common forms of boiler-work. The first* is that of the tubular boiler already illustrated in § 15.

SPECIFICATION FOR A HORIZONTAL TUBULAR STEAM-BOILER.

Type.—Boiler to be of the horizontal tubular type, with overhanging front and doors complete.

Dimensions.—Boiler to be 16 feet 3 inches long outside, and 60 inches in diameter. Tube-heads to be 15 feet apart outside.

Steam-dome to be 33 inches in diameter and 33 inches high.

Tubes—How Set and Fastened.—Boiler to contain 66 best lap-welded tubes, 3 inches in diameter by 15 feet long, set in vertical and

* See *Am. Engineer*, Nov. 1883: Specifications by the Hartford Inspection and Insurance Co.

horizontal rows, with a space between them, vertically and horizontally, of not less than one inch (1"), except the central vertical space, which is to be two inches (2"), as shown in drawing. Tubes to be set sufficiently high from bottom of boiler to give room for man-hole and access to boiler underneath tubes, as shown in drawing. No tube to be nearer than 3 inches to shell of boiler. Holes through heads to be neatly chamfered off. All tubes to be set by a Dudgeon expander, and slightly flared at the front end, but turned over or beaded down at back end.

FOR IRON PLATES.

Quality and Thickness of Iron Plates.—Shell plates to be of an inch thick, of the best C. H. No. 1 iron, with brand, tensile strength, and name of maker plainly stamped on each plate. Tensile strength to be not less than 50,000 pounds per square inch of section, with a good percentage of ductility. Heads to be of an inch thick, of the best C. H. No. 1 flange-iron.

FOR STEEL.

Steel Plates.—Shell-plates to be of an inch thick, of homogeneous steel of uniform quality, having a tensile strength of not less than 60,000 pounds per square inch of section, nor more than 65,000 pounds with 45 per cent ductility, as indicated by the contraction of area at point of fracture under test. Name of maker, brand, and tensile strength to be plainly stamped on each plate. Heads to be of same quality as plates of shell in all particulars, of an inch thick.

Flanges.—All flanges to be turned in a neat manner to an internal radius of not less than two inches (2"), and to be clear of cracks, checks, or flaws.

Riveting.—Boiler to be riveted with ¾-inch rivets throughout. All girth seams to be single-riveted. All horizontal seams and flange of dome at junction of shell of boiler to be double staggered riveted. Rivet-holes to be punched or drilled so as to come fair in construction. *No drift-pin to be used in construction of boiler.* A reamer to be used in all cases to bring the holes "fair."

Braces.—There are to be twenty-two (22) braces in boiler—seven (7) on each head above the tubes, and six (6) on rear head and two (2) on front head below the tubes, as shown in drawing, none of which are to be less than three (3) feet long. Braces to be made of best round iron, of one (1) inch in diameter, and of single lengths.

How Set and Fastened.—There are to be five (5) lengths of T-iron, four (4) inches broad and one half (½) inch thick, Three (3) being eight (8) inches long, Two (2) being fourteen (14) inches long, placed radially, and riveted with ¾-inch rivets to each head above the tubes, as shown

in drawing. There are to be four (4) lengths of T-iron, four (4) inches broad and one half (½) inch thick, two (2) being six (6) inches long and two (2) being twelve (12) inches long, placed radially, and riveted on rear head below the tubes, also two (2) lengths, six (6) inches long, riveted on front head below the tubes, each side of man-hole, as shown in drawing. The holes for fastening the braces to these radial brace-bars are all to be drilled. The braces are to be fastened with suitable jaws and turned pins or bolts, so as to realize strength equal to inch-round iron. Braces to be set as shown in drawing, and to bear uniform tension, and to be fastened on shell of boiler with two (2) ¾-inch rivets each.

Dome.—Dome to be constructed of same quality of iron or steel as heads of boiler, of an inch thick, and head to be of same quality of iron or steel as heads of boiler, of an inch thick. Dome-head to be braced with six (6) ¾-inch braces, reaching from head well down on shell, as shown in drawing, and fastened at each head with two (2) ¾-inch rivets. Opening from boiler into dome to be inches in diameter. There are to be two pieces of T-iron riveted on to outside of boiler shell, within the dome girthwise, one on each side of opening, as shown in drawing; also suitable drip-holes to be cut at junction of shell and dome.

Man-holes.—Boiler to have two man-holes, each eleven (11) inches by fifteen (15) inches, with strong internal frames (as shown in drawing), and suitable plates, yokes, and bolts, the proportions of the whole such as will make them as strong as any other section of the shell of like area. One to be placed in front head underneath the tubes, and one to be placed on shell of boiler, as shown in drawing.

Hand-holes.—Boiler to have one hand-hole, with suitable plate, yoke, and bolt, located in rear head below the tubes, as shown in the drawing.

Nozzles.—Boiler to have two cast-iron nozzles, four (4) inches internal diameter, one for steam and the other for safety-valve connections, securely riveted to head of dome, as shown in drawing.

Wall-plates.—Boiler to have four cast lugs, two on each side, securely riveted in place, each twelve (12) inches long, with a projection of nine (9) inches from the boiler, the rear lugs each to rest on three transverse rollers, one inch in diameter, which are to rest on suitable cast-iron wall-plates, as shown in drawing, front lugs to rest on suitable wall-plates, without rollers.

Blow-out.—For blow-out connection, one plate, one half inch thick, to be secured with rivets driven flush on inside of the shell, and tapped to receive a two (2) inch blow-pipe.

Front.—Boiler to be provided with cast-iron front and all the requisite doors and fastenings for facility of access to tubes, furnace, and

ash-pit. All to be of substantial construction, neat appearance, and close-fitting.

Buckstaves—Grate-bars.—Boiler to be provided with buckstaves; also all bolts, rods, nuts, and washers, anchor-bolts to extend in setting beyond bridge-wall; also bearer and grate bars (pattern to be selected); also cast-iron door, to be at least two (2) feet by three (3) feet and provided with liner plate, for back tube-door—and door fifteen inches by fifteen inches for flue for side or rear end.

Fittings.—Boiler to be provided with one safety-valve, inches in diameter, one inch steam-gauge of standard make, three gauge-cocks properly located, also one glass water-gauge, a two-inch open-way blow-valve, and feed and check valves, each one and one quarter inch. Feed to be introduced into front head of boiler, above tubes. Feed-pipe to extend well back towards rear of boiler, across tubes, and turn down between tubes and shell, as shown in drawing.

Fusible Plug.—Boiler to be provided with a fusible plug so located that its centre shall be two inches above upper row of tubes at back end.

Damper.—Boiler to be provided with a damper with suitable hand attachments, easily accessible at the front of the boiler, damper to be fitted to the throat of the smoke-arch, as near as practicable to the tube-openings, and of area equal to the cross-section of all the tubes.

The size and description of parts to conform substantially to the details of the accompanying plan. All the above to be delivered at

and all the material and workmanship to be subjected to inspection and approval.

The following are specifications for a marine flue-boiler for river service:*

Specification for Flue-boiler.

There is to be one boiler of the flue and return-tube type, of the following general dimensions:

Extreme length	13 feet.
Diameter of shell	8 "
Width of front	8 "
Diameter of steam-chimney	5 "
Diameter of steam-chimney lining	3 "
Height of steam-chimney above shell	5 "

* For very elaborate and complete naval specifications, see Shock's "Treatise on Steam Boilers." New York: D. Van Nostrand.

There are to be two furnaces, each forty-two inches wide and six feet long. Bottom of furnace-legs to drop six inches below shell. Bridge-wall seven inches thick. Combustion-chamber of back furnaces in one twenty-four inches deep. Back connection twenty-eight inches deep. Front connection twenty-eight inches deep. Furnace-crowns to be a semi-circle. To have two 16-inch, two 12-inch, two 11-inch, and four 9-inch direct flues, all fifteen inches long, and ninety return tubes, seven feet ten inches long.

All the horizontal shell-seams to be double-riveted, also the bottom course of steam-chimney where riveted to shell and vertical seams. Back part of furnace, where connected to shell, to be double-riveted one third distance around, the remainder of riveting about the boiler to be single.

Thickness of Plates.—To be as follows: tube-sheets $\frac{7}{16}$, shell of boiler (round part) $\frac{3}{8}$, bottom course of steam-chimney $\frac{7}{16}$, inside lining of steam-chimney $\frac{3}{8}$, the balance of the iron in the boiler to be $\frac{5}{16}$, except bottoms of furnace-legs, which are to be $\frac{3}{8}$.

Material.—Furnaces to be of steel, and the balance of the iron in the boiler to be of the best C. H. No. 1, and flange-iron, and all stamped 50,000 pounds T. S. All flat surfaces to be braced $6\frac{1}{2}$-inch centres, with hot sockets wherever practicable.

Boiler to be fitted with man-hole in top of shell, also in front in the spandrels over furnace-crowns. Openings to be surrounded by a wrought-iron ring $2\frac{1}{2}$ inches wide by $\frac{3}{4}$ inch thick, riveted to shell. Hand-holes to be cut in legs and every part where necessary to facilitate cleaning. Man and hand holes to be furnished with plates and bolts complete.

Front connection to be fitted with wrought-iron doors, fitted with wrought-iron linings, and fitted with two registers. Furnace-doors to be of wrought-iron with cast-iron perforated linings, to be fitted with wrought-iron hinges, latches, etc., complete. A suitable opening with door to be provided in back connection.

Grates and Bearers.—Boiler to set on three cast-iron legs under furnaces running the whole length, about 12 inches high, and fitted with supports for grate-bar bearers. Grates to be 6 feet long in two lengths. Ash-pans of cast-iron to be laid in brick and cement. Back ends of legs to be closed in with No. 10 sheet-iron.

Shell of boiler to rest on a cast-iron saddle in two halves firmly bolted.

Test.—The boiler before being hoisted into the vessel is to be subjected to a hydrostatic pressure of 100 pounds per square inch.

Boiler Connections.—Smoke-pipe 36 inches diameter, and to extend 16 feet above top of steam-chimney, to be made of No. 12 iron, to be finished with angle-iron top, bead-iron joints, six chain-stays and damper, arranged to be operated from the fire-room. Lower part of smoke-pipe

to be bolted to the steam-chimney, the inside lining being carried up for this purpose. Chain-stays to be provided with turn buckles to take up the slack.

Steam-chimney to be encased with No. 16 sheet-iron and fitted with a stopping-cap in two halves. A chamber of cast-iron is to be bolted to the steam-chimney, containing the safety-valve and stop-valve, each to be five inches in diameter, with top of trumpet shape. Surface and bottom blows to be provided with screw stop-valve for the former and cock for the latter, secured on the boiler. Blows to be led out of the vessel below the water-line through a suitable valve.

There is to be a feed-valve on each side of boiler in front, in connection with check-valve, one to be for the donkey and the other for the main feed-pumps, both to be of composition and 2 inches diameter. Gauge-cocks and glass water-gauge to be placed on a stand-pipe, connected to the boiler. Boiler to be covered with 1½-inch felt, canvased and painted, felt to be secured with necessary bands around steam-chimney.

Steam Pump.—To be an approved steam-pump with 2½-inch water-plunger, and fitted with hand-gear. To be connected with necessary receiving-pipes from bilge and sea cock, and delivery-pipes to boiler, overboard and for fire hose, each branch to be fitted with a proper screw-valve. Exhaust-pipe to lead overboard, awash with water-line; all the donkey pump-pipes to be of wrought-iron, galvanized.

The following is a general proposal-specification for "sectional boilers," purposely left somewhat elastic to admit all bidders: *

SECTIONAL STEAM-BOILERS.

Boilers.—Proposals will be received for two (2) sectional or water-tube steam-boilers of nine hundred (900) superficial feet of heating-surface each, or eighteen hundred (1800) superficial feet of heating in the aggregate for both boilers.

Details.—The proposals must be for the two (2) steam-boilers complete with cast-iron fronts, grate bars and bearers, ash-pit and side doors and frames, steam and water gauges, check and blow-off valves, safety-valves of the pop pattern, smoke connection for chimney, damper and rods, and a steam main connected with the steam drums of the two boilers, together with all bolts, beam-columns and materials necessary for the proper erection of said boilers upon the grounds of the gas company in the city of Cincinnati.

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* Issued by the Cincinnati Gas Co., as prepared by Mr. J. W. Hill, 1883.

Erection.—The proposals must embrace the construction, erection, and trimming of said boilers complete, excepting connection of steam-main with company's steam-pipe. The contractors to turn over the plants to the company ready for use.

Tubes.—The tubes in the boilers shall be lap-welded, of three and one half (3.5) inches, or four (4) inches, external diameter (at the option of the contractor), of such length and arrangement in connection with steam and water drums as may seem proper to the contractor.

Steam Drums.—The steam-drums shall be twenty-eight (28) inches diameter, of Otis or equivalent soft steel plates, of a tensile strength of seventy thousand (70,000) pounds per square inch of section, of three-eighths (.375) inch thickness, with double-riveted longitudinal seams, and furnished with heads corresponding in quality and strength with the steel shell.

Steam Mains.—The steam-mains shall be eighteen (18) inches diameter, of Otis or equivalent steel plates, of a tensile strength of seventy thousand (70,000) pounds per square inch of section, of one quarter (.25) inch thickness, with double-riveted longitudinal seams, and with heads corresponding in quality and strength with the steel shell.

Water Drums.—The water-drums may be of cast-iron or wrought-iron, at the option of the contractor, of sixteen (16) inches diameter, and shall be of same relative strength as the steam-drums.

Sample Joint.—Each proposal shall be accompanied by a sample joint, such as will be used in connecting the tubes to the headers, or to the steam and water pumps; and shall contain a detailed schedule (written or printed) of all the material dimensions of parts subject to strain, (pressure) and shall be accompanied by a scale-drawing [one and one half (1.5) inches to the foot] of front elevation, transverse and longitudinal sections, and plan of boilers set in brick-work ready for smoke connections with chimney.

Chimney.—The company will furnish a brick chimney, properly located, octagonal in form, of an internal cross-section of twelve (12) superficial feet, increasing gradually in internal diameter from bottom to top, and ninety (90) feet six (6) inches high from level of boiler-house floor.

Heating Surface.—The proposals must state exact heating-surface, measured upon inner diameter of tubes, and outer diameter of steam-drums (or steam and water drums).

Grate Surface.—Grate-surface and area of cross-section of smallest throat through which the hot gases must pass to chimney, and area of cross-section of smoke connection with chimney to be stated.

Smoke Holes.—(The openings one upon either side of stack to receive the smoke connections will have an area of six (6) superficial feet each, and will be two (2) feet wide horizontal diameter, and three and forty-

three hundredths (3.43) feet long vertical diameter, with semicircular ends struck upon a radius of one (1) foot.)

Fuel.—The fuel to be fired under the boilers will be "Breeze" or coke screenings, a smokeless fuel containing from twelve (12) to fifteen (15) per cent of non-combustible matter.

Guarantees.—Each proposal must contain a guarantee of capacity of not less than four (4) pounds of steam per hour per superficial foot of heating-surface, with moderate firing; and shall contain a guarantee of economy of not less than eight (8) pounds of steam exclusive of water (if any) entrained from and at 212° Fahr. per pound of "Breeze."

Test Trial.—When the boilers are erected and completed, a test-trial for capacity and economy shall be made by the contractor, under direction of the company.

Failure to Comply.—Should the boilers fail to comply with the contractors' guarantees for economy or (and) capacity, or in any other respect, a reasonable time not in excess of sixty (60) days shall be given the contractor to remedy such defects; failing in which the boilers and all appurtenances belonging thereto and furnished by the contractor shall, at the option of the company, be removed within thirty (30) days from order of such removal.

Time.—The proposal must name the time after acceptance required for completion of boilers as per invitation.

Terms of Payment.—One half of the contract price for said boilers will be paid upon completion, and after the test-trial and acceptance as herein provided; and the balance within thirty (30) days thereafter. The company reserves the right to reject any or all proposals submitted.

The following are two dimension-specifications of boilers and locomotives as issued by the Pennsylvania Railway Motive Power Department:

STANDARD P. R. R. CLASS "R" FREIGHT ENGINE WITH TENDER.

Boiler material,	Steel.
Thickness of boiler-sheets, dome, and extended smoke-box,	$\frac{5}{16}$ in.
Thickness of boiler-sheets, barrel,	$\frac{7}{16}$ in.
" " " outside fire-box,	$\frac{5}{8}$ in.
" " " smoke-box, sheet under dome, waist, and throat,	$\frac{1}{2}$ in.
Max. internal diameter of boiler, Belpaire fire-box,	$60\frac{3}{4}$ in.
Min. internal diameter of boiler, Belpaire fire-box,	59 in.
Height to centre of boiler, from top of rail,	89 in.
No. of tubes,	183.

nside diameter of tubes,	$2\frac{1}{4}$ in.
Outside " "	$2\frac{1}{2}$ in.
Tube material,	Wrought-iron.
Length of tubes between tube-sheets,	$156\frac{13}{16}$ in.
External heating-surface of tubes,	1,564.24 sq. ft.
Fire-area through tubes,	5 sq. ft.
Length of fire-box at bottom (inside),	107 in.
Width of " " "	42 in.
Height of crown-sheet, above top of grate (centre of fire-box),	$51\frac{1}{2}$ in.
Inside fire-box material,	Steel.
Thickness of inside fire-box sheets, sides,	$\frac{1}{4}$ in.
" " " " front, back, and crown,	$\frac{5}{16}$ in.
Thickness of tube-sheets,	$\frac{1}{2}$ in.
Tube-sheet material,	Steel.
Heating-surface of fire-box,	166.8 sq. ft.
Total heating-surface,	1,731.04 sq. ft.
Fire-grate area,	31.1 sq. ft.
Max. diameter of smoke-stack, } Conical,	$26\frac{5}{8}$ in.
Min. " " " } Conical,	18 in.

STANDARD P. R. R. CLASS "P" PASSENGER ENGINE WITH TENDER.

Boiler material,	Steel.
Thickness of boiler-sheets, dome,	$\frac{5}{16}$ in.
" " " barrel, and outside fire-box,	$\frac{3}{8}$ in.
Thickness of boiler-sheets, slope, roof, waist, and smoke-box,	$\frac{7}{16}$ in.
Max. internal diameter of boiler, } Wagon-top,	$56\frac{3}{8}$ in.
Min. " " " } Wagon-top,	$53\frac{1}{4}$ in.
Height to centre of boiler from top of rail,	$86\frac{1}{2}$ in.
No. of tubes,	240.
Inside diameter of tubes,	$1\frac{3}{4}$ in.
Outside " "	2 in.
Tube material,	Wrought-iron.
Length of tubes between tube-sheets,	$130\frac{7}{16}$ in.
External heating-surface of tubes,	1,365.81 sq. ft.
Fire-area through tubes,	4 sq. ft.
Length of fire-box at bottom (inside),	9 ft. $11\frac{7}{8}$ in.
Width " " " "	3 ft. $5\frac{3}{4}$ in.
Height of crown-sheet above top of grate, centre of fire-box,	3 ft. 10 in.
Inside fire-box material,	Steel.
Thickness of inside fire-box sheets, sides,	$\frac{1}{4}$ in.
" " " front, back, and crown,	$\frac{5}{16}$ in.
Thickness of tube-sheets,	$\frac{1}{2}$ in.
Tube-sheet material,	Steel.

Heating-surface of fire-box,	164.39 sq. ft.
Total heating-surface,	1,530.2 sq. ft.
Fire-grate area,	34.8 sq. ft.
Diameter of smoke-stack (straight),	18 in.
Height of stack above top of rail,	15 ft. 0 in.

204. Quality of Material and methods of test are often specified very minutely, and are sometimes settled by legal provisions. Thus the British "Admiralty" issue the following requirements, other than the ordinary tensile tests, for test of irons:

Samples of B. B. iron 1 inch (2.54 centimetres) thick are to bend cold, without fracture, to an angle of 15° with the grain and 5° across the grain; ½ inch (1.27 centimetres) plates, 35° and 15° respectively; $\frac{3}{16}$ inch (0.48 centimetre) and under must bend 90° and 40°. When hot, plates 1 inch (2.54 centimetres) and under must bend 125° with and 90° across the grain.

For B. iron, the requirements are:

THICKNESS. Inches.	Centimetres.	ANGLE. With the grain.	ANGLE. Across the grain.
1	2.54	10°	5°
½	1.27	30°	10°
$\frac{3}{16}$	0.48 and under.	75°	30°

Test-pieces to be 4 feet (1.22 metres) long with the grain and full width of plate across the grain.

The plate should be bent from 3 to 6 inches (7.62 to 15.24 centimetres) from the edge.

The Admiralty tests for steel are the following when selecting mild-steel ship-plates:

Tenacity from 26 to 30 tons per square inch (4100 to 4700 kilogrammes per square centimetre). Extension at least 20 per cent in a length of 8 inches (19.3 centimetres).

Longitudinal strips planed down, 1½ inches (3.8 centimetres) wide, heated to low cherry-red, cooled in water 82° Fahr. (28° Cent.), must bend, in the press, to a curve of radius equal to one and a half times the thickness.

Plates must be free from lamination and injurious surface defects.

One plate in every fifty in any invoice is to be tested.

Test-pieces to be 8 inches (20.32 centimetres) long, or more, and parallel.

Weight is estimated at forty pounds per square foot for one inch thick, with a variation allowable of 5 per cent (lighter weight only) on plates of half inch thick or thicker.

The same specifications apply to bulb, bar, and angle steel.

Lloyd's rules allow for one ton higher tenacity and one half the bend specified by the Admiralty. Masts and yards are to be made of iron having a tenacity of 20 tons per square inch (3150 kilogrammes per square centimetre).

In working, all plates and bars are to be bent cold when possible, and heating only resorted to when unavoidable. All parts that have been heated must be annealed as a whole, if possible, and if not, a little at a time. When necessary, long pieces may be made up of shorter ones with butted joints shifted and strapped securely. No pieces failing in the working can be used, but samples must be cut from them and forwarded to the Admiralty for examination. Work must be finished above a black heat. Hammering is objected to, and the hydraulic press used for bending when practicable.

An American railroad makes the following specifications for materials supplied to the repair-shops:

Specifications for Common Bar Iron.—Grain.—To be uniform and fibrous, rather than granular in texture. *Workmanship.*—All bars to be smoothly rolled and to be accurately gauged to size ordered. *Tensile Strength.*—To average 55,000 pounds per square inch (3,867 kilogrammes per square centimetre), and no iron to be received less than 50,000 pounds to square inch (3,515 kilogrammes per square centimetre). *Working Test.*—A three-quarter-inch bar bent double, cold, to show no fracture; the same bar, heated, to be bent and also to be drawn to a point showing no tendency to "red-shortness."

Specifications for Stay-bolt Iron.—Grain.—To be uniform and of a fibrous nature. Iron to be soft and easily worked. *Tensile Strength.*—To be 60,000 pounds to the square inch (4218 kilogrammes per square centimetre). *Working Test.*—A bar three-quarter inch diameter to be bent cold, showing no flaw; a piece of same diameter, having thread cut on it, may

show opening when bent double, cold, but such opening should not extend more than one eighth of an inch in depth. When put into the boiler the metal should not become brittle when hammered down to form a head.

205. **The Duties of the Inspector** are such as demand the utmost care, considerable skill, and a large amount of experience, together with a good judgment and absolute conscientiousness. He must also be a man of sufficient strength of character to do his duty by his employers, whatever influences may be brought to bear upon him to induce him to pass work or material which does not fully comply with the specification. He is expected to examine all material with a view to the determination, both of its full compliance with the terms of the specification and contract, and of its general fitness for the work.

The first step in inspection is a careful measurement of the piece offered for examination, and a comparison with the drawing, model, pattern, or template, to ascertain if it is made exactly to size.

Exact workmanship is often secured by a system of standard gauges. This is especially the case where machines are made in large numbers. The modern method of manufacturing machinery for the market compels the adaptation of special tools to the making of special parts of the machines, and the appropriation of a certain portion of the establishment to the production of each of these pieces, while the assembling of the parts to make the complete machine takes place in a room set apart for that purpose. But this plan makes it necessary that every individual piece of any one kind shall fit every individual piece of a certain other kind without expenditure of time and labor in adapting each to the other.

This requirement, in turn, makes it necessary that every piece, and every face and angle, and every hole and every pin in every piece, shall be made precisely of this standard size, without comparison with the part with which it is to be paired; and this last condition compels the construction of gauges giving the exact size to which the workman or the machine must bring each dimension.

Sizes being found right, the quality of the material is

determined by examination and test; defective welds, lamination, and cracks are found and condemned. A blow with a hammer often reveals unsoundness, and a laminated plate may be detected by suspending it and tapping it all over. If the defect appears on the surface, the sheet may be supported by the corners in the horizontal position, and water poured on it at the line indicating lamination, and then tapping it with a hammer. The liquid will work into the sheet, lifting the surface lamina and revealing the extent of the defect.

CHAPTER XII.

THE MANAGEMENT AND CARE OF BOILERS.

206. The Management of Steam Boilers, it may be stated generally, demands in the highest degree care, conscientiousness, and unintermitted vigilance. The value of the property entrusted to the attendants is so great and the consequences of ignorance or neglect in operation are so serious, and may be so disastrous, that no possible excuse can be given for negligence on the part of the proprietor or his responsible representative, in securing intelligent, experienced, and trustworthy attendants, or on the part of the attendants, whether engineer in charge, fireman (" stoker"), or water-tender, in the management of the boiler.

The care demanded, in ordinary working, to keep a full supply of water, to preserve the fires in their most effective condition, to keep an even steam-pressure, an ample and unintermittent supply of steam, is such as tries the best of men; but, added to this, it is imperative that the responsible man in charge of boilers have that presence of mind and readiness in action and promptness in expedients, in time of accident or of emergency, which is hardly less necessary than on the battlefield. In still further addition to these requirements, any person taking charge of boilers must understand so much of the trades of the boiler-maker and the machinist that he can if necessary make minor repairs, reconstruct his feed-apparatus, and refit the valves. He must know something of the nature and of the peculiar methods of combustion of all ordinary fuels, and enough of the principles of combustion to be able to realize the waste that may follow the introduction of an excess of air on the one hand or the production of incomplete combustion on the other, and enough of the nature and dangers of sediment and incrustation to understand the necessity of adopting the usual expedients for prevention.

He should know how to adjust the safety-valve, and should understand its office and the liability to accident coming of its maladjustment or neglect.

Intelligence, experience, and conscientiousness are the best and only real insurance against accident.

207. **Starting Fires** is an art which is not always familiar to even experienced firemen. With the soft coals it is only necessary to have a supply of some kind of kindling material that can be lighted by a match or a lamp, and to begin by building with it a small fire and then adding a little coal, and thus gradually increasing the flame-bed until the grate is fully covered with the burning fuel. On a large grate the whole area is usually first covered with fuel, from end to end and side to side, so that no currents of air can enter the boiler through the ash-pit, and so as to insure that all air entering the furnace may pass over the wood used in kindling the fire. The wood is placed on the front of the bed of coals, with oily cotton-waste, shavings, small chips, or other easily ignited material under it. The ash-pit doors are kept closed until the fire is fairly burning, so that the draught may be concentrated on the point at which the flame is started. After a few minutes, the fire being well started, the upper part of the mass burning in front is pushed back over the grate, and the flame is rapidly communicated to the whole bed of fuel. When this is effected the ash-pit doors are opened and the fire managed in the customary way. The precaution must be taken to see that the air has free access to the boiler-room and to the furnace.

The process just described will work well with anthracite coal; but the operation is a slower one, and more wood is usually required.

Building a fire of wood and then gradually adding coal is a more expeditious method than the above, but it is less economical.

When it is known that steam will be needed the boiler should be at once closed up and filled, in order that, should a leak be discovered or a misfit occur in setting a man-hole or a hand-hole plate, time may be allowed to get it right without causing delay in getting up steam. A leak discovered after

steam has been raised may sometimes be checked by driving in pine wedges. The rubber "gaskets" used in making the joints under man-hole and hand-hole plates may be "blackleaded" on one side to prevent their adhering to the boiler. All valves should be carefully examined before starting fires, and especial care should be taken to see that the safety-valves and the feed-check valves are in good order. All flues should be clean, and every part of the boiler and all its accessories should be given a last and thorough inspection.

Before starting the fires the precaution should be taken to see that the fuel is not allowed to be placed in the furnaces until the boilers have been filled with water; even the kindling material should never be permitted in an empty boiler. The fires should not be forced at the first, as hot gases passing over heating-surfaces in contact with cold water, and the sudden expansion due to too rapid increase of temperature, may cause strain and leakage.

208. **The Management of Fires** is an important but often neglected branch of instruction in fitting firemen for their special duties. The economy of boiler management is very largely dependent upon the skilful handling of the fuel and the furnace. In general, the fires should be kept of even thickness, clear of ash and clinkers, and as clean at the sides and in the corners as elsewhere. The depth of the fuel is determined by its nature and size and by the intensity of the draught. Hard coals can be used in greater depth than soft, and large coal in deeper fuel-beds than small. A strong draught demands a thick fire, a mild draught a thin one. With a low chimney and natural draught small anthracite or fine bituminous coal may be most successfully burned in a layer but a hand's breadth in thickness; while with large "steamboat" coal of the hardest varieties and with a heavy forced draught, fires have been actually worked successfully of five times that depth, or more. The secret of success in handling fires is to find the best depth of fire for the conditions existing; to keep that thickness at all times, allowing for the ash that may accumulate; to throw the fuel on the grate at such frequent intervals as will prevent the fire burning into holes or in irregular thickness at different points; to introduce

the coal so quickly and with such exactness of direction that no serious loss may occur from the inrush of cold air, and so that every shovelful should go precisely where needed, the place for the next shovelful being at the same instant located. The removal of ash is best done by means of a rake or other tool used under the grate, rather than by stirring and breaking up the bed of fuel by working through the furnace-door. The various forms of shaking grate now in use are often very efficient. For best working, the fire should usually be kept bright beneath, and the ash-pit clear. With light draught, however, and thin fires, it is sometimes advisable, if sufficient steam can be so made, to allow the fire to be less frequently raked out, and some accumulation of ash may be thus produced when working with maximum economy.

"Firing," or "stoking," as the replenishing of the fuel is called, must be done very quickly and skilfully to avoid serious annoyance by variation of steam-pressure and supply. Where several furnaces are in use this difficulty is less likely to be met with, as the fires may be cooled and cleaned in rotation. A skilful man will find it possible to keep steam very steadily with but two furnaces, even.

Ash-pits should not be allowed to become filled with ashes, as the result would be the checking of the draught, the reduction of the steaming capacity of the boiler, and loss of efficiency, even if not the melting down of the grates. It is customary at sea to clean out the ash-pits and send up ashes, throwing them overboard once in every watch of four hours, when in full steaming. If much unburned fuel is found in the ashes, it should be, if possible, cleaned out and returned to the fire, or used elsewhere. The gases should have 10 per cent CO_2, usually.

Cleaning fires consists in thoroughly breaking up the mass of fuel on the grate, shaking out all the ashes, quickly raking out all "clinker," as the semi-fused masses of ash and fuel are called, and, after getting a level, clean bed of good fuel, as promptly as possible covering the whole with a layer of fresh coal. This is done, usually, once in four hours at sea and twice a day on land; but different fuels require somewhat different treatment. The work should be performed with the greatest

possible thoroughness and dispatch, to avoid serious loss of steam-pressure.

Mr. C. W. Williams' instructions for handling the fires, where bituminous coal is used and an air-supply above the fuel is provided, are substantially as follows:

Charge the furnace from the bridge-end, gradually adding fuel until the dead-plate is reached and the whole grate evenly covered. Never permit the fire to get lower than four or five inches in thickness, of clear and incandescent fuel, uniformly distributed, and laid with especial care along the sides and in the corners. Any tendency to burn into holes must be checked by filling the hollows and securing a level surface. All lumps should be broken until not larger than a man's fist. Clean out the ash-pit so often that there shall be no danger of overheating the grate-bars.

An ash-pit, brightly and uniformly lighted by the fire above, indicates that it is in good order and working well. A dark or irregularly lighted ash-pit is indicative of an uncleaned and badly working fire. The cleaning of the fire is best done, in ordinary working, by a "rake" or other tool working on the under side of the grates, and not by a "slice-bar" driven into the mass of fuel and above the grate.

209. **Different Fuels** require different treatment. The principles just stated apply generally, but more, perhaps, to anthracite coals. The soft coals are commonly so disposed on the fire that a charge may have time to coke and its gases to burn before it is spread over the grate; liquid fuels must be so supplied that they may burn completely, at a perfectly uniform rate, and especially in such manner as to be safe from explosive combustion; the same precaution is demanded with the gaseous fuels. Special arrangements of grate and a special routine in working may be, and often are, demanded in such cases.*

210. **The Liquid and Gaseous Fuels** are often and successfully burned in conjunction with solid fuels. In such cases the same methods are to be adopted and precautions observed in handling the latter as when burned alone.

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* For the peculiarities of these fuels and their use, see Chap. III.

The liquid fuels are almost invariably the crude petroleums. They are sometimes burned in a furnace in which they are allowed to drip from shelf to shelf in a series arranged vertically at the front of the furnace, the flame passing to the rear, with the entering current of air supporting their combustion. In many cases they are sprayed into the furnace by a jet of steam which should be superheated and at high pressure. The use of the steam is considered to have a peculiar and beneficial effect, possibly through chemical reactions facilitating the formation of hydrocarbons. The petroleums are all liable to cause accident if carelessly handled, and special precaution must be observed in their application to the production of steam.

The gaseous fuels are seldom used under steam-boilers, except where "natural" gas from gas-wells is obtainable, or where a very large demand or the use of metallurgical processes justifies the construction of gas-generators. Even greater precautions against accidents by explosion are needed than with the liquid fuels. In burning gas, maximum economy is secured by careful apportionment of the air-supply to the gas-consumption, and especially in avoiding excess. The regenerator system is not generally economically applicable to boilers.

211. **The Solid Fuels,** coal and wood, are burned in furnaces which are proportioned especially for the intended fuel. With soft coals, the grate-bars are set closer together than for hard coals; the provision for the introduction of air above the grate is larger, and a "dead-plate" is usually provided on which to coke the coal. In the use of this device, the fresh fuel is piled on the dead-plate at the furnace-mouth, and then left until the next charge is to be thrown in; the first is then pushed in and spread over the fire, and the second charge is coked. In some cases the fuel is replenished on one side of the fire at a time; but oftener it is spread over the whole surface of the grate.

A furnace for burning wood is deeper than one intended for coal. Wood burns so freely that the ingoing charges must be continually replaced by fresh fuel.

212. **The Operation of the Boiler,** aside from the management of the fires, in such manner as to make steam regu-

larly and in ample quantity, mainly consists in adjusting the draught so as to make the production of steam keep exact pace with the demand, and in keeping the supply of feed-water as precisely proportional to the amount demanded, and thus preserving the water constantly at a safe level, and reducing to a minimum the danger, on the one hand, of uncovering heating surfaces, and on the other of causing heavy "priming" or foaming, or the production of wet steam. As the working conditions of a steam-boiler are always those of steady motion, constant vigilance and an undisturbed and unconquerable equilibrium of mind on the part of the attendants are essential to perfect safety and thorough efficiency.

So long as the water is kept at the proper height in the boiler, the boiler itself being in good repair, safety is assured; and if the steam-pressure can be held at the proper point, efficiency is equally well insured; but to maintain a state of absolute safety and efficiency, it is essential that something more than careful feeding and skilful firing be practised. Every apparatus upon which the working of the boiler is in any degree dependent must be *known* to be in good order and absolutely reliable. Feed-pumps must be kept in good repair, well packed, and ready for service on the instant; the safety-valve must, by at least daily trial, be seen to be in good working order; the pressure-gauges must be frequently compared with a standard test-gauge to make certain that its error—it will usually have some error—is known and unimportant; and the gauge-cocks and water-gauge glass—the latter, especially, is liable to deceive—must be tried often and their reliability made evident.

Blow-off and feed valves often leak, must be often examined, and should be repaired or reground whenever perceptibly affecting the water-supply. A grain of sand or a chip under a valve has sometimes given rise to unfortunate results.

In salt water, when using sea-water in the boilers, frequently blowing off from the bottom or a continuous discharge from the "surface-blow" or "scum-pipes" is essential to keeping the water so fresh as not to produce deposits or incrustation. The higher the "saturation" permitted, however, provided that

common salt is not actually deposited, the less the expense of operation and the less the amount of lime-scale formed. About twelve times the quantity of salt found in sea-water is thus the maximum; and three or four is probably as high as is safe, two thirds the water entering the boiler being converted into steam, the remaining third blown out into the sea again. And generally, if n represent the ratio of saltness of boiler to that of the sea, and m the ratio of feed-water blown out to that made into steam,

$$m = \frac{1}{n - 1}; \quad n = \frac{1}{m} + 1;$$

and if the ratio of total feed-water to total evaporation is p,

$$p = \frac{m + 1}{1} = \frac{n}{n - 1}.$$

If large boiler-power is demanded, and a battery consisting of a considerable number of boilers is in use, one man should be detailed especially to see that the water is properly supplied; he is called the "water-tender." On a large steamer several are often employed, each caring for a set of boilers and supervising the firemen or "stokers" and coal-handlers employed at his section. All these workmen should be carefully chosen, and known to be skilful and trustworthy. A careless or unskilful man will waste vastly more in bad firing than can be saved in the difference of wages between a good and an inefficient man. One good man should handle a ton of coal an hour—several times the value of his own wages—the total charges for the boiler-room amounting usually to about one fourth or one fifth wages, three fourths or four fifths fuel, and wear and tear. The coal-handler should be able to supply two to four firemen, according to distance of coal-bunkers and convenience of transportation.

Firing—stoking—should be done with promptness and precision during a few seconds, while the nearest man holds the furnace-door open. Every moment of needless delay allows great volumes of cold air to rush into the furnace, reducing the

efficiency of the boiler and causing strain by cooling the surfaces just before exposed to gases of high temperature. The damper should be partly closed while working the fire. With a number of furnaces the order of opening the furnace-doors may be systematically arranged, and a very noticeable saving thus effected.

213. **A Forced Draught** is produced by the use of a blower or fan, or by the steam-jet. The former is the best method where practicable. In using the forced draught, the fires should be managed precisely as with a natural draught; but the rate of combustion is so greatly increased that they must be made heavier, and the process of replenishing the fuel even more carefully conducted. The draught should—indeed must—usually be checked while adding fuel; but where the closed fire-room or stoke-hole is adopted, or with the steam-jet, this is not absolutely necessary, though best both on the ground of economy and of safety. When the blast is driven into the ash-pit, care should be taken to open the ash-pit doors the instant the fan is stopped, or danger is incurred of melting down the grate-bars by the intense heat concentrated beneath them, untempered by the entering current of cold air.

214. **Closed and Open Boiler-rooms**, with forced draught, have each their advantages and their special methods of management. With the closed, air-tight, fire-room all air supplied to the fire passes through the room, ventilating it thoroughly and cooling it, while at the same time enabling the fires to be worked precisely as where a natural draught is employed. No peculiarities of management are introduced other than come of the rapidity of combustion. In providing for the opening and closing of the fire-room doors for entrance and exit of the attendants, a double system must be so arranged that one will always act as a valve to close communication with adjacent apartments. In putting on and taking off the blast the fan should be first "slowed down," the doors then opened, and finally the blower stopped. In putting on the blast these steps should be precisely reversed.

With the open boiler-room and closed conducting passages leading from fan to ash-pit, the special precautions to be taken

are simply to open the ash-pit the instant the blast is stopped, or to start the blower the instant the ash-pit doors are shut.

215. **The Regulation of the Steam-pressure** should be effected by varying the intensity of the draught by means of the damper at the chimney, or, where a forced draught is employed, by properly adjusting the speed of the blower; it should never be attempted, except in a serious emergency, to regulate it by opening furnace, ash-pit, or "connection" doors. The latter method is certain to accelerate corrosion, strain the seams, and produce leakage of tubes, as well as to waste fuel. The rushing of currents of air, alternately cold and hot, through the flues and over the heating-surfaces has been found in some cases to have probably been the cause of injury leading to explosion; and the introduction of cold air over the fire is invariably a cause of serious loss of economy of fuel.

Automatic dampers, if well made and reliable, are very useful.

216. **The Control of Water-supply** should always be entrusted only to experienced and proven men; this is the main precaution to be taken in every case. The more uniform the supply, and the more perfectly the proper water-level is maintained, the safer and the more economical the operation of the boiler. It is better that the feed-water be supplied continuously than to feed intermittently. Steam is then made more regularly, and of better quality; the heating of the feed is more steady and more thorough; the boiler itself suffers less from varying temperatures, either local or general; and every operation goes on more easily and more satisfactorily.

The feed-pump, if used, should be amply large for cases of emergency, but should be ordinarily worked continuously and slowly; the injector, if employed, should be of such size that it may never cease working while the boiler is in normal operation; and a second instrument or, better, an independent feed-pump, should be always ready for use should occasion arise. The necessity for watchfulness is greater with boilers having small water-space for their power, as the modern tubular and sectional boilers, than in the older types, in which the regulating effect of a large body of water is felt.

The first duty of engineer or of fireman, on taking charge of a boiler, for the day or for a watch, is to see that the water is at the right height; and his constant care throughout the whole period for which he is responsible is to keep it right, and to provide against any contingency that may introduce a liability of its rising or falling beyond the intended and safe range of fluctuation.

217. **Emergencies** are liable to arise unexpectedly in the operation of the steam-boiler and demand the highest qualities of mind and character on the part of him who may be called upon to meet them. Self-possession and coolness, with full control of every faculty, will usually enable the attendant to successfully meet any form in which they may appear, with the single exception of an explosion of the boiler; for that case prevention is the only cure. Minor emergencies occur so frequently that the experienced engineer or fireman will generally meet them promptly and effectively, and greater events often find him equally ready and prompt of action. Every attendant, whether in engine or boiler-room, should have constantly in mind the best course to take in the event of any accident; and every intelligent and conscientious man will have often gone over, in his own mind, the methods and means by which he should attempt to prevent every probable accident, or to render its consequences as unimportant as possible. There is often no time to think, and whatever is to be attempted can only be done intuitively, on the instant, on the impulse of the moment, guided by earlier thought or earlier experience. This quality of readiness in emergencies is perhaps the most valuable of all those especially required in the management of engines, boilers, and machinery generally.

218. "**Low-water**" is the most serious and trying of the conditions liable to arise in steam-boiler management. Once the water-level has fallen below that of the crown-sheet or the upper row of tubes, but one thing can be done—reduce the temperature of the furnace and flues as rapidly as possible to a safe point. To introduce a larger quantity of feed might cause a sudden and dangerous increase of pressure by flooding the overheated metal; to attempt to haul out the fires might pro-

duce a similar effect by the momentarily higher temperature often caused by breaking up the bed of fuel, and by the prolonged exposure of the already endangered metal it might cause the hot sheets or flues to give way. The proper course to pursue is at once to dampen the fires, preferably by quickly covering them with wet ashes. Coolness, promptness, and rapidity of action are the only safeguards in this case. With high steam-pressure, the danger is that the overheated and softened and weakened sheets may be forced out; the introduction of the feed-water is in itself a less serious source of danger. The Author has many times, in experimental work, pumped water into a red-hot boiler,* but has only once seen an explosion so produced. He has experimentally allowed the water to be completely evaporated from an outside-fired boiler, and has then succeeded in covering the fires with ashes and refilling the boiler without injury.† When the boiler has cooled down and no steam is forming, it will be safe to blow off steam, then haul fires, blow out the water, and examine to see if any injury has occurred.

Dangers of this kind rarely arise where the gauges are kept in order; but carelessness in regard to the water-gauges and gauge-cocks is said to be a more frequent cause of accident than all other causes combined. Equal care should be taken to see that the fusible plugs, if used, are clean and in good condition.

219. Priming or Foaming takes places whenever the quantity of steam drawn from the boiler exceeds that which can be liberated, dry, from the mass of water which it at the time contains. This action may be due either to forcing the boiler beyond its real capacity, or to the presence of foreign matters in solution, which tend to cause the retention of the bubbles of steam in the mass, and, when leaving it, to carry spray into the steam-space. A boiler will foam badly if the design and construction are such that a rapid circulation is not insured, sufficient to carry all steam made below the upper level freely to the sur-

* In the work of the U. S. Commission on Steam-boiler Explosions, 1875.

† This might not be as safe an operation with an inside-fired boiler.

face, where it may be naturally discharged; or where currents conflict; and where a mass of water, entangled among the tubes or flues, finds no natural way of egress, laden as it is with the steam bubbles which convert it into foam; and priming may thus occur, even when the boiler is working well within its rated capacity. Any boiler will foam if overworked.

Priming is also produced by the presence of mucilaginous, oily, or other foreign matter in the water; or by changing from a salt-water feed to fresh-water, and sometimes by the reverse; by sudden and heavy demand for steam at the engine, or by suddenly and widely opening the safety-valve; and by other causes less well understood. When foaming takes place, it often throws water from the boiler so rapidly and in such quantities that the engine may be liable to have a cylinder-head knocked out, and the height of the water-level in the boiler may be dangerously lowered. The instant such dangers arise the throttle-valve should be partly closed, when the water will usually immediately settle down in the boiler, making it possible to ascertain its height in the gauges. If dangerously low,—a rare occurrence, however,—proceed as already indicated; if otherwise, the draught should be promptly lessened, the fires checked, and, by thus reducing the quantity of steam made, the production of foaming and its attendant dangers may be quickly stopped. If the cause is suspected to be dirty water, continuous feeding and blowing, and thus changing the water, should be resorted to to remove that cause of danger. With boilers heavily driven, as is usual at sea, and too common elsewhere, priming is always one of those contingencies which those in charge of the boilers must be prepared to meet. Where surface-condensers are used and the boiler is fed with water of unchanging and pure quality, foaming rarely occurs.

The method of circulation of water in a plain cylindrical or other "outside-fired" boiler, and the course of the steam produced, is well illustrated in the accompanying figure, the fire being assumed to be located at the left. The greater part of the steam made in the boiler is produced immediately over the fire, here assumed to be at the left, and rises at once, as seen, into the steam-space above, thus determining the circulation

in currents rising at that end and falling at the rear end of the boiler. In all cases the rising currents are at the hottest part, the descending currents at the cooler portions of the boiler. Were a boiler so constructed as to be uniformly heated, an efficient circulation would not be obtainable.

"False water" is a term applied to the apparent increase of volume of the water in a boiler when priming takes place. It may be imperceptible; but it often causes an apparent rising of the water-level to the extent of several inches. It is considered that a well-proportioned boiler should be capable of evaporating five times the volume of its own steam-space each minute

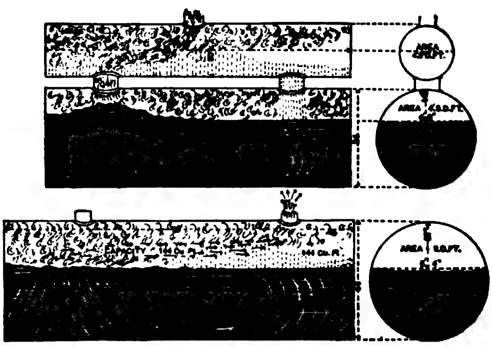

FIG. 117.—CIRCULATION OF WATER AND STEAM.

without serious priming; but it is not thought wise to attempt an evaporation exceeding one half this amount.

220. Fractures, whether of seams, sheets, or tubes, are liable to occur in all boilers; but the danger is diminished as the care taken in selection of material is the greater, the construction better, and the management more intelligent. Such injuries rarely occur so suddenly or are so extensive as to be immediately dangerous, and ample time is commonly allowed for their detection and safe remedy. Cracks in sheets or seams are repaired by patching and in tubes by plugging each end, or by the removal of the sheet or tube. The duty of the attendant, for the moment, is to reduce steam-pressure at once, and as soon as possible blow off steam, to empty the boiler and to see it

properly repaired—temporarily if necessary, but preferably permanently. A blistered sheet should be treated as if fractured.

221. **A Deranged Safety-valve** may sometimes cause danger by making it difficult to reduce the steam-pressure or to keep it below a dangerous point. This is sometimes a consequence of the rusting of the stem or of the valve and its sticking to its seat, or in such a manner that an insufficient area for exit is obtainable. In such a case the steps to be taken are to check the fires, to reduce the production of steam, and to find other directions of egress, as through gauge-cocks, all available valves, by the engines taking steam from the boiler, and by means, even, of their cylinder, water, and drip cocks, until the safety-valve can be made to work or until the steam can be disposed of in other ways. If the valve be daily or oftener raised to its full height, no such danger will be incurred.

222. **The General Care** of a steam-boiler demands much experience, some knowledge of the causes and the methods of prevention and of remedy of injury, and thorough reliability on the part of those to whom it is entrusted. Aside from the injuries and the deterioration which occur in its daily operation, there are others which are to be anticipated quite independently, and which may become even more serious when the boiler is out of use: these are principally the various forms and consequences of corrosion. Such general care includes the preservation of the boiler against decay or loss of efficiency, the retention of its setting in good repair, and the keeping in order of all its accessories and connections.

223. **The Chemistry of Corrosion** has been studied by many distinguished modern chemists, and is now well understood. Corrosion of iron and steel and the changes which characterize that method of deterioration cannot go on in the air except when both moisture and carbonic acid are present, or unless the temperature is considerably higher than that of the atmosphere. When exposed to the action of free oxygen, however, under either of these conditions, the metal is corroded—rusts—rapidly or slowly, according to its purity. Wrought-iron rusts quickly in damp situations, and especially when near decaying wood or other source of carbonic acid;

while steels are corroded with less rapidity, and cast-iron is comparatively little acted upon. The presence of acids in the atmosphere accelerates corrosion, and the smoke of sulphur-charged coal, or smoke charged with pyroligneous acid, frequently causes the oxidation of out-of-door iron structures.

The composition of the rust forming upon surfaces of iron is determined by the method of oxidation, but is principally peroxide of iron. Calvert gives the following:

	Rust from Conway Bridge.	Llangollen.
Fe_2O_3	93.094	92.900
FeO	5.810	6.177
Carbonate of iron	0.900	0.617
Silica	0.196	0.121
Ammonia	traces	traces
Carbonate of lime		0.295

A series of experiments made to determine the effect of different oxidizing media, after four months' exposure of clean iron and steel blades, gave results * indicating that oxidation is principally due to the presence of carbonic acid with oxygen.

When distilled water was deprived of its gases by boiling, and a bright blade introduced, it became in the course of a few days here and there covered with rust. The spots where the oxidation had taken place were found to mark impurities in the iron, which had induced a galvanic action, precisely as a mere trace of zinc placed on one end of the blade would establish a voltaic current.

224. **The Methods of Corrosion** vary with circumstances. Kent has shown † that the rusting of iron railroad bridges is sometimes greatly accelerated by the action of the sulphurous gases and the acids contained in the smoke issuing from the locomotive, and that sulphurous acid rapidly changes to sulphuric acid in the presence of iron and moisture, thus greatly accelerating corrosion. Iron and steel absorb acids, both gaseous and liquid, and are therefore probably permanently injured whenever exposed to them.

Calvert experimented upon iron immersed in water contain-

* *Chemical News*, 1870–71.

† *Iron Age*, 1875.

ing carbonic acid, in sea-water, and in very dilute solutions of hydrochloric, sulphuric, and acetic acids. A piece of cast-iron placed in a dilute acetic-acid solution for two years was reduced in weight from 15.324 grammes to $3\frac{1}{2}$ grammes, and in specific gravity from 7.858 to 2.631, while the bulk and outward shape remained the same. The iron had gradually been dissolved or extracted from the mass, and in its place remained a carbon compound of less specific weight and small cohesive force. The original cast-iron contained 95 per cent of iron and 3 per cent of carbon, the new compound only 80 per cent of iron and 11 per cent of carbon. Iron immersed in water containing carbonic acid was also found to oxidize rapidly. Iron exposed to the wash of the warm aerated water of the jet-condensers of steam-engines is often very rapidly oxidized, and the mass remaining after a few years often has the appearance, texture, and softness of plumbago, so completely is the iron removed and the carbon isolated.

Mallett, experimenting for the British Association,* found the rate of corrosion of cast-iron greatly accelerated by irregular and rapid cooling, and retarded by a slow and uniform reduction of temperature while in the mould.

The rate of corrosion is usually nearly constant for long periods of time, but it is retarded by removal of the coating formed by the rust, as if left it creates a voltaic couple, which accelerates corrosion.

Hard iron, free from graphite, but rich in combined carbon, rusts with least rapidity, and with about equal rapidity in the sea as in the air, in an insular climate. Two metals of different character as to composition or texture being in contact, the one is protected at the expense of the other. Foul sea-water, as "bilge-water," corrodes iron very rapidly.

The rate of corrosion of iron is too variable to permit any statement of general application. In several cases the plates of iron ships have been found to be reduced in thickness in the bilges and along the keel-strake, at the rate of 0.0025 inch (0.06 millimetres) per year, as ordinarily protected by paint;

* Proc. Inst. C. E. 1843.

while it is stated that iron roofs, exposed to the smoke of locomotives, have sometimes lasted but four years.

The iron hulls of heavy iron-clads have sometimes been locally corroded through in a single cruise, where peculiarities of composition or of structure, or the proximity of copper or of masses of iron of different grade or quality, had caused local action.

225. **Durability of Iron and Steel.**—Twaite* gives the following as the measure of the probable years' life of iron and steel undergoing corrosion, assuming the metal to be uniform in thickness. Thin parts corrode most rapidly.

$$T = \frac{W}{CL},$$

in which W is the weight of the metal in pounds, of one foot in length of the surface exposed; L is the length in feet, of its perimeter; and C a constant, of which the following are values:

VALUES OF *C*.

MATERIAL IN	SEA WATER.		RIVER WATER.		IMPURE AIR.	AVERAGE SEA WATER.
	Foul.	Clear.	Foul.	Clear, or in air.		
Cast-iron	.0656	.0635	.0381	.0113	.0476	.....
Wrought-iron	.1956	.1255	.1440	.0123	.1254	.....
Steel	.1944	.0970	.1133	.0125	.1252	.....
Cast-iron, skin removed	.2301	.0880	.0728	.0109	.0854	.....
" galvanized	.0895	.0359	.0371	.0048	.0199	.....
" in contact with brass, copper, or gun-bronze						0.19 to 0.35
Wrought-iron in contact with brass, copper, or gun-bronze						0.30 to 0.45

When wear is added to the effect of oxidization, the "life" of a piece of iron or steel may be greatly shortened. If kept well painted, multiply the result by two.

The mean duration of rails of Bessemer steel is, according to experiments in Germany, about sixteen years. Ten years of trial at Oberhausen, on an experimental section of the

* Molesworth, p. 32, 21st ed., 1882.

line between Cologne and Minden, has shown that the renewals during the period of trial were 76.7 per cent of the rails of iron of fine grain, 63.3 of those of cementation steel, 33.3 per cent of those of puddled steel, and 3.4 per cent Bessemer steel.

226. **The Preservation of Iron and Steel** is accomplished usually by painting, sometimes by plating it.

As the more porous varieties will absorb gases freely and some liquids to a moderate extent, Sterling has proposed to saturate the metal with mineral oil; heating the iron and forcing the liquid into the pores by external fluid pressure, after first freeing the pores from air by an air-pump, or other convenient means of securing a vacuum in the inclosing chamber.

Temperatures of 300° to 350° Fahr. (150° to 177° Cent.) and pressures of 10 to 20 atmospheres are said to be sufficient for all purposes.

Voltaic action may be relied upon to protect iron against corrosion in some situations. Zinc is introduced into steam-boilers for the double purpose of preventing corrosion and of checking the deposition of scale. It is sometimes useful in the open air, where rusting is so seriously objectionable as to justify the use of so expensive a preventive. The zinc itself is often quickly destroyed.

Zinc has been used as a plating, or sheathing, on iron ships, as by the plan proposed by Daft,* and in some cases with good results.

Mallett has proposed the use of lime-water to check the internal corrosion of the bottoms of iron ships where exposed to the action of bilge-water, and uses a solution of the oxychloride of copper, or other poisonous metallic salts, in the paint applied externally, to check fouling and consequent oxidation; the amalgam of zinc and mercury is also sometimes used to protect iron plates.

227. **The Paints and Preservation Compositions** in use are very numerous: Coal-tar, asphaltum, and the mineral oils are all used, the latter having the advantage, in the crude state, of being free from oxygen and having no tendency to absorb it.

The animal and vegetable fats and oils are used temporarily in many cases, and if free from acid, are useful.

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* Fouling and Corrosion of Iron Ships. London. 1867.

Surfaces of iron are painted with red-lead and oil, with oxide of iron mixed with oil, or with oxide of zinc similarly prepared.

Sterling prepares a varnish by dissolving gum copal in paraffine oil, placing the iron in it, and heating it under increased pressure. Iron vessels, tinned inside, which can be hermetically sealed, are used, heated by superheated steam. Scott uses the following mixture:

Coal tar	6	gallons.
Black varnish	3	"
Wood-tar oil	2	"
Japanese glue	1	"
Red lead	28	lbs.
Portland cement	14	"
Arsenic	14	"

The Author has used fish-oil as a preservative of steam-boilers out of use for long periods of time, with success, and has found some vegetable paints of unknown composition far more durable, when exposed to the weather, than red-lead and oil.

"Iron paints" bear heat well, and are often better than any other cheap paint. Iron to be painted should first be carefully cleaned by scraping and washing, and then coated once or twice with linseed-oil. One pound of good oxide of iron paint should cover 20 square yards (16.7 square metres) of iron.

Where practicable the Barff method of protection may be adopted for small parts. It consists in heating the iron or steel to be treated to a temperature of 500° Fahr. (260° Cent.) in an atmosphere of steam, and thus securing an even and impermeable coating of the black (ferric) oxide.

Where more complete protection is demanded, the iron is heated to 1200° Fahr. (649° Cent.), and is said to be thus made impregnable against the attack of even the acrid vapors of the chemical laboratory.

Steam-boilers are preserved, in mass, against corrosion by various special methods. They are sometimes dried thoroughly by means of stoves, if necessary, and then closed up with a quantity of caustic lime in their water-bottoms or lower water-

spaces. Occasional inspection prevents injury occurring undetected in any case.

When new boilers are stored they are usually painted inside and out. Air should be excluded from them by closing all man-holes, etc. Working boilers are best preserved by a thin coating of scale on their heating-surfaces. Mineral oils being used for lubrication of their engines, decay is far less likely to take place rapidly. Steel corrodes more rapidly than iron, and the common brands of iron corrode less than the finer. Zinc placed within boilers, and in amount one thirty-fifth the area of the heating-surface, was found, by the British Admiralty, to protect them perfectly. A pound (0.45 kilogrammes) of carbonate of soda to every ton (or *tonne*) of coal burned is ordered to be pumped into boilers at sea, to give the water an alkaline reaction. Boilers of sea-going vessels average a life of nine or ten years.

Boiler Coverings having for their object the protection of the external surfaces against loss of heat and from any injurious action liable to occur in consequence of their exposure, are of very various kinds, and are always considered the better the more perfect they are as non-conductors. Care should be taken, however, that they do not themselves cause injury more serious than that which they are designed to prevent. Hair-felt has been known to cause—possibly by some peculiar galvanic or electric action—observable acceleration of corrosion on the inner sides of the sheets to the exterior of which it has been applied, as, for example, where used to cover the steam-drums of marine boilers; mineral-wool, when containing sulphur-compounds, has been known to absorb moisture, and to thus cause rapid corrosion of parts with which it was in contact. When free from sulphur no such danger is incurred. They should be air-tight.

The experiments of Mr. C. E. Emery give the following as the relative values of available covering materials:*

* Trans. Am. Society Mech. Engrs., vol. ii., 1881.

Non-Conductor.	Value.	Non-Conductor.	Value.	Non-Conductor.	Value.
Wood-felt.	1.000	Charcoal	.632	Asbestos	.363
Mineral-wool No. 2	.832	Pine-wood across fibre.	.553	Coal-ashes	.345
Do. with tar	.715	Loam, dry and open	.550	Coke in lumps	.277
Sawdust	.680	Slacked lime	.480	Air-space, undivided	.136
Mineral-wool No. 1	.676	Gas-house carbon	.470		

Hair or wool felt is injured by high temperature; woods are liable to char, and all organic matters, in presence of grease and dampness, to take fire spontaneously. Asbestos is much used, as is also "rock-wool," which is less likely to absorb moisture than the "mineral-wool" from the blast-furnaces. Sand, ashes, and other earthy matters are often used to fill in over boilers. They are, however, liable to conceal and accelerate corrosion whenever leakage takes place beneath them. In all cases the values of successive layers of non-conductor decrease in a geometric ratio. Anything that will encage air in its pores is a good covering. Large boilers and their pipes, as designed by Mr. E. D. Leavitt, Jr., were covered with about two inches and a half of plaster and sawdust, and one inch of hair-felt outside that. The proportion of the mixture is about one part of plaster and two parts of sawdust. The plaster and the sawdust are mixed up like mortar. They are first put in together dry, and then wet and mixed up. For steam-pipes, the mixture is applied from one and a half to two and a half inches thick.

For boilers, wooden battens $\frac{3}{4}$ by $2\frac{1}{2}$ inches wide are used. Between the edge of the batten and the boiler half an inch of the compound is put. These are fastened all around the boiler; then a band of hoop-iron is put around it, and filled between the battens with plaster. The practice of putting it on in little blocks about a foot square has been adopted. Outside of that, the specifications call for an inch of hair-felt and canvas.*

228. Leakage, and contact of damp portions of supports and setting, produce the most serious corrosion. A leak, once started, will keep everything near it damp, and thus cause acceleration of oxidation to a very marked degree. Where the leakage, or the dampness produced by it, finds its way between the iron of the boiler and the brickwork about it, there is no

* Trans. Am. Soc. Mech. Engrs., 1882.

opportunity of evaporation and drying the moistened surfaces, and the dampness thus held in contact with the metal promotes decay. When inspecting the boiler, care should be taken to detect every such cause of deterioration, and to immediately repair the injured part. It is well to so design and construct the boiler that there will be as little liability as possible to this kind of injury.

229. **Galvanic Action** is liable to occur, and enormously to accelerate corrosion, either local or general, whenever a mass of brass, bronze, or copper, large or small, is in metallic contact with the boiler at any point, or with any of its connections. The brass tubes of a surface-condenser have been often known to thus cause the ruin of a boiler in a few months, and very serious general corrosion in few weeks. Copper boiler-tubes, brass valve-seats, and any other minor part made of such electro-negative metals, may similarly cause local deterioration and leakage or weakness. The remedy is either to remove the cause of the trouble; to protect the metal attacked, as by allowing it to become coated with a thin layer of incrustation; or to counteract the effect of the electro-negative metal by introducing a mass of another element, as zinc, which is electro-positive to both the iron of the boiler and the copper or other material producing the destructive action. In the latter case, the zinc will be corroded instead of the iron of the boiler, and must be occasionally renewed.

230. **Incrustation and Sediment** are deposited in boilers, the one by the precipitation of mineral or other salts previously held in solution in the feed-water, the other by the deposition of mineral insoluble matters, usually earths, carried into it in suspension or mechanical admixture. Occasionally also vegetable matter of a glutinous nature is held in solution in the feed-water, and, precipitated by heat or concentration, covers the heating-surfaces with a coating almost impermeable to heat and hence liable to cause an overheating that may be very dangerous to the structure. A powdery mineral deposit sometimes met with is equally dangerous, and for the same reason. The animal and vegetable oils and greases carried over from the condenser or feed-water heater are also very likely to cause

trouble. Only mineral oils should be permitted to be thus introduced, and that in minimum quantity. Both the efficiency and the safety of the boiler are endangered by any of these deposits.

The amount of the foreign matter brought into the steam-boiler is often enormously great. A boiler of 100 horse-power uses, as an average, probably a ton and a half of water per hour, or not far from 400 tons (406 *tonnes*) per month, steaming ten hours per day, and, even with water as pure as the Croton at New York, receives 90 pounds (41 kgs.) of mineral matter, and from many spring waters a ton (1.016 *tonnes*), which must be either blown out or deposited. These impurities are usually either calcium carbonate or calcium sulphate, or a mixture; the first is most common on land, the second at sea. Organic matters often harden these mineral scales, and make them more difficult of removal. Mineral oils often soften them.

The only positive and certain remedy for incrustation and sediment once deposited is periodical removal by mechanical means, at sufficiently frequent intervals to insure against injury by too great accumulation. Between times, some good may be done by special expedients suited to the individual case. No one process and no one antidote will suffice for all cases.

Where carbonate of lime exists, sal-ammoniac may be used as a preventive of incrustation, a double decomposition occurring, resulting in the production of ammonium carbonate and calcium chloride—both of which are soluble, and the first of which is volatile. The bicarbonate may be in part precipitated before use by heating to the boiling-point, and thus breaking up the salt and precipitating the insoluble carbonate. Solutions of caustic lime and metallic zinc act in the same manner. Waters containing tannic acid and the acid juices of oak, sumach, logwood, hemlock, and other woods, are sometimes employed, but are apt to injure the iron of the boiler, as may acetic or other acid contained in the various saccharine matters often introduced into the boiler to prevent scale, and which also make the lime-sulphate scale more troublesome than when clean. Organic matters should never be used.

The sulphate scale is sometimes attacked by the carbonate

of soda, the products being a soluble sodium sulphate and a pulverulent insoluble calcium carbonate, which settles to the bottom like other sediments and is easily washed off the heating-surfaces. Barium chloride acts similarly, producing barium sulphate and calcium chloride. All the alkalies are used at times to reduce incrustations of calcium sulphate, as is pure crude petroleum, the tannate of soda, and other chemicals.

Marine boilers have been effectively treated for the prevention or the removal of scale, by introducing sheet-zinc, or zinc in balls or in blocks of any convenient size and form. The incrustation met with in marine boilers, properly managed, being always nearly pure sulphate of lime, the zinc, probably by some voltaic action, causes the deposit to become pulverulent, instead of compact, and very hard and strong, as when formed in the unprotected boiler, and it also compels the precipitation of the mineral upon the zinc itself principally. The water in boilers of any kind is very liable at times to become acidified perceptibly by the decomposition of the lubricants entering with the feed-water from the engine cylinders and condensers, and corrosion is thus accelerated. In such cases the zinc suffers and the boiler is preserved, if metallic contact is secured between the iron or steel and the zinc—precisely as, when the boiler itself is constructed of different qualities of metal, one part is preserved while another part is corroded. Zinc, as, relatively, an electro-positive metal, protects iron; which latter is electro-negative to the former, and takes the hydrogen of so much water as may be decomposed by the voltaic action occurring, the zinc being attacked by the oxygen set free on that element of the voltaic pile so formed. Marine boilers thus protected have shown no trace of decay after years of use.

Whenever zinc is used, the precaution should be taken to secure a perfect metallic connection between it and the boiler; otherwise it will be neither uniform in action nor reliable. The zinc is sometimes amalgamated to prevent wasteful oxidation by local action.

A little soda, or sodium carbonate, introduced into the boiler may often insure the formation of a softer deposit where it is found to be hard, and to so incrust and embalm the zinc

that it ceases to do its work. A surface of zinc of 25 to 50 square inches (2.5 to 4.5 square decimetres, nearly) per ton of water contained in the boiler, and per month, is usually found ample.

After studying the use of zinc as an "anti-incrustator," and the reports of M. Lesueur, who first introduced it extensively in France,* M. Euvrard concludes that it should be used in the form of "pigs" or ingots, and in any type or in any part of a boiler, although it is better not to place it on the heating-surfaces of the firebox. He advises from one pound to two pounds for every ten square feet of heating-surface at a time ($\frac{1}{2}$ to 1 kg. per sq. m.). It is found that zinc is valuable with calcareous feed-waters when not excessively hard, causing the deposit to become pulverulent, and thus altering an incrustation or scale into a sediment.

Water-tube Boilers have been successfully treated by M. C. Quehaut,† where the incrustation was calcareous, and largely consisting of calcic sulphate, by using instead of the "tartrifuges" commonly employed for such cases, none of which proved satisfactory, sheet-zinc of thickness No. 18. Sheets about two metres (6.56 feet) long and 0.8 metre (3 feet) wide were cut into strips each about $\frac{1}{12}$ metre (3.28 inches) wide, and wrapped helically on a mandril, forming coils of which about 45 kilograms (100 pounds) were introduced into a boiler rated at 40 horse-power at each charge. The making of the coils cost about one dollar. One of the strips so coiled was pushed into each tube after each cleaning, and withdrawn at the succeeding period of washing out. Heavier zinc did not answer as well, as the strips were liable to be displaced by the circulating current.

Incrustation takes place on the zinc instead of upon the adjacent iron surfaces. It is pulverulent, and easily removed. The cost was $2.50 per annum per horse-power.

231. Repairs are the source of the great expense of maintenance of steam-boilers, and sometimes of new dangers hardly less serious than those which they are expected to prevent.

* Annales des Mines, 1877; Jour. Franklin Inst. 1878.

† Ann. de l'Association des Ingénieurs de Liège, 4me série, t. v., 1886.

Frequent and systematic inspection and test will always reveal the approaching necessity of repairs long before serious risks are run, and, if promptly attended to and skilfully performed, the life of the boiler may often be very greatly prolonged. At sea it is customary to have on hand a good stock of extra boiler-plate, rivets, tubes, and other material for use in making repairs, and to have all minor and temporary repairs made by the engineer's crew. On land this is rarely necessary, as boiler-makers are usually close at hand, and the work can be done more perfectly, quickly, and cheaply by regularly employed workmen.

Leaky tubes are often plugged until it becomes convenient to replace them by new ones. In such cases wooden or iron plugs are driven into the ends, and leakage thus checked. Sometimes special apparatus, devised with a view to convenience of application while steam is still kept on, are employed. Local defects, as oxidation or blisters, are remedied by bolting on "soft-patches" of boiler-plate fitted to the weakened surface and made tight by a cement of red-lead and oil, or a mixture of red and white lead and oil, with iron borings and some other constituent, as sal-ammoniac, the effect of which is to promote the oxidation of the borings and the production of a hard, stone-like cement. A permanent "job" is made by cutting out the defective metal, and riveting in a piece of new boiler-plate, thus making a "hard-patch." A patch secured by tap-bolts is also sometimes called a "hard-patch."

Leaks in steam-pipes are stopped by placing sheet-rubber packing over the crack or joint, covering this with sheet copper or brass, and wrapping with tightly wound wire or cord. Feed-pipes may be similarly temporarily repaired, or by covering the leak with a "putty" of red and white lead and wrapping it with canvas and twine.

Where a crack appears in any part of the heating-surface, if not more than two or three inches long, it should be stopped by drilling at each end and inserting a screw-plug. A long crack must be patched. Hard-patches are used when in contact with the fire; soft-patches elsewhere:

232. **Inspection and Tests** of strength should be occa-

sionally resorted to for the purpose of determining the precise condition of the boiler at the time, and its absolute safety under the conditions of its regular use. Custom and opinion differ somewhat, among the ablest and most experienced engineers, as to the precise method and the extent to which such examinations and tests should be carried. It may be safely assumed, however, that the following principles and processes will be considered as, at least, on the safe side.

The complete visual inspection and examination of a boiler, inside and out, should be considered one of the primary duties of the person responsible for its safe operation at every available opportunity, and during its operation a watchful eye should be kept upon it uninterruptedly. With marine boilers, a complete examination is expected to be made every time that steam is off—usually at the end of every trip; stationary and locomotive boilers are inspected at regular intervals by skilled inspectors or by the master-mechanic having charge of them. The former should be so examined at least once in each three months, and a complete inspection and thorough test should be made as often as once a year; the latter still oftener demands attention.

In a careful inspection, the inspector goes underneath and examines all the fire-sheets, and inside and with hammer and chisel and lamp examines every portion of the boiler. If a corroded or grooved place is found, or a blister, it receives careful attention. If for any reason the examination should be made more complete, the hydrostatic test is applied. In the course of the examination, the safety-valves, the gauge-cocks, water-gauges, feed and stop valves, pumps, dampers, every detail, should receive careful attention. The tap of the hammer will, to the experienced ear—and inspection should only be intrusted to experienced men—reveal the thickness of a sheet, the presence of a crack, groove, or any form of serious oxidation or injury, the soundness of stays and braces and their connections, and the nature and extent of any defect that may exist. After this inspection the defects, if any, are removed, and after the repairs are completed the inspection should be repeated to make sure that the work has all been done, and

properly done. Finally, the boiler is closed, filled to the safety-valve, all stop-valves being closed, and is subjected to a pressure exceeding its working pressure by at least one half, and preferably more. Many authorities advise a double pressure. While this operation is going on, the inspector carefully watches to see that no new weakness is revealed.

That testing by hydraulic pressure is not alone sufficient to reveal dangerous defects or to insure against disaster is unquestionable. The Author has repeatedly met with evidence that explosions have occurred at pressures less than those at which tests had been made; and it is well known to experienced engineers, and especially to inspectors, that a dangerously thin boiler may sustain high pressures for a time. A case is related * in which a water-pressure of 12 atmospheres was sustained by a boiler which in places was exceedingly thin, and, as reported, at several points not thicker than paper. It not infrequently occurs that the inspector's hammer is driven through sheets by which very considerable pressures had been sustained.

It was at one time common to test boilers to three times their working pressure, or even more; but it is less usual now. The United States regulations controlling steam-vessels prescribe a ratio of 1½ to 1; French regulations direct that a ratio of 2 to 1 shall be adopted for new boilers, annually, on naval vessels, and the same on merchant vessels at first, but later reduced the ratio to 1½ to 1, although even then this pressure must not be kept up more than five minutes.† The British regulations prescribe 2 to 1, the tests to be made semi-annually. If signs of weakness are observed the pressure may be reduced. All boilers should be drilled occasionally wherever thinness of plate is suspected. All such tests and inspections should be made before painting, and inspection should be made while the boiler is still under the test-pressure. Leaks are often more easily detected under cold water than under steam-pressure; and the inspection rather than the test is the insurance against accident. This inspection and the hammer-test are especially relied upon where the boiler is one with the his-

* *Locomotive*, Sept. 1873, p. 3.

† Ledieu, Appareils à Vapeur, vol. ii.

tory of which the inspector is unfamiliar, and when old and worn; as it is only by this plan that cracks, leaks, blisters, distortion of parts, and corrosion can be satisfactorily found and gauged.

All boilers are usually very carefully inspected inside and out at least once a year, and thoroughly tested. It is customary to make quarterly examinations also as complete as possible, but not, as a rule, to make the extended inspection and test which is insisted upon at the annual inspection. Where the feed-water is impure, however, and where sediment and incrustation are found to give occasion, these periodical examinations should be made so frequently that all possible danger may be avoided. Every boiler should be cleaned out and thoroughly freed from incrustation at intervals—whether a year, a month, or a week—such as will secure immunity from danger of overheating and from serious loss of economy.

233. **General Instructions** for the management and care of boilers should always be written out and placed in the hands of attendants whenever they are not known to be in every respect familiar with their duties. Especially should they be cautioned against raising steam too rapidly, or emptying the boiler while the setting is hot, and against pumping cold water in large quantities into a hot boiler, and other errors of either omission or commission by which the boilers may be injured. All air-leaks about the setting should be found and stopped. The most perfect cleanliness should be enjoined.

The most complete codes of instructions are those issued to naval officers, of one of which the following is an abstract:*

The engineer officers are to make themselves acquainted with the general construction and with any special fitting of the boilers under their care. In order to protect the plates and stays from corrosion, it is essential that the interior surfaces should be coated with some impervious substance. A thin layer of hard scale, deposited by working the boilers with sea-water, has been found to be the most effectual preservative; and therefore all boilers when new, or at any time when any of

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* *London Engineering*, 1884.

the plates or stays are bare, are to be worked for a short time with the water at a density of about *three* times that of sea-water, until a slight protective scale has been deposited; but in this case care is to be taken not to allow a scale to be formed of such a thickness as would in an appreciable degree impair the efficiency and economy of the boilers. During the first six months' service the boilers should be frequently examined; and afterwards, where possible, at least once a month, or after steaming twelve days. The boilers are to be examined carefully after steaming; and every judicious measure is to be used for the prevention and removal of scale, especially on the furnace crowns and sides. Whenever serious corrosive action has been discovered it is to be at once reported, together with full information as to the circumstances and the supposed cause. The tubes and tube-plates are to be cleaned as soon as possible after steaming.

It is essential that at first the water should be kept for a short time at about three times the density of sea-water, until the thin protective scale has been formed, as before directed. After this, in the ordinary working of the boilers, the engineer officers in charge of machinery are to use their discretion as to the most suitable density at which the water in the boilers should be kept for the service on which the ship is employed. This density, which is in no case to exceed three times, nor be less than one and a half times that of sea-water, will probably vary to some extent, on different stations and under different conditions of working, of regular service, and the engineer officers will be guided in their selection of the working density by their experience of the economy of fuel under steam, and of the state of the boilers after steaming. No tallow or oil of animal or vegetable origin is to be put into the boilers to prevent priming, nor for any other purpose whatever.

When the boilers are empty, the fires are not to be kept laid; the boilers are to be kept dry and warm; all accessible parts are to be frequently examined and cleaned; and the lower parts are to be coated with red and white lead, or other protecting substance. Where the boilers cannot be kept *thor-*

oughly dry and warm, they are, at the discretion of the engineer officer in charge, to be kept *quite full.**

The boilers should not be exposed to sudden changes of temperature; the steam should not be raised rapidly; the smokebox doors should not be opened suddenly, as a rush of cold air through the tubes affects the ends—and the tubes leak; and the stop and safety valves should be opened gradually. The safety-valves should be partially raised each watch to test the fittings, and the smokebox doors should not be opened except when absolutely necessary. The blow-off cocks are to be kept in good condition.

The spaces at the backs and sides of the boilers are at all times to be kept clear; and on no account is anything combustible to be placed on the top of the boilers or in contact with them. Every care is to be taken to prevent any accumulation of soot or coal-dust between the uptake and casings of the boilers, and, when necessary, means should be provided for examining the air-space between the uptake and the air-casing, and every possible precaution taken to prevent the clothing of the boilers being set on fire.

It is well to keep a log in the boiler-room, where a large "plant" is operated, and the record so kept should exhibit all important data relating to its operation. The following is a good form of ruling for the blanks or log-book employed:

BOILER RECORD.—Week Ending ________________ 188

No. of Boiler.	Average Pressure.	Hours Steaming.	Coal, Tons.	Ashes Removed	Water Used.	Remarks.
Totals..						

Memoranda.—

* A small quantity of washing soda or other alkali may be introduced with advantage.

CHAPTER XIII.

THE EFFICIENCIES OF STEAM-BOILERS.

234. **Steam-boiler Efficiency** is not difficult of definition when the nature of the quantity to be measured is itself first understood. There are, however, as will be presently seen, several different efficiencies of the steam-boiler, as of the steam-engine; and it is important that each be distinctly defined before a study of either, or of total efficiency, can be made. In general, it may be said that efficiency is measured by the ratio, in common or similar and definitely related terms, of a result produced to the cost of its production. As, in the study of the steam-engine, either efficiency is measured by the ratio of work done in the specified manner to the work or work-equivalent expended in doing it; so, in the case of the steam-boiler, either efficiency is measured by the ratio of a heat-effect, or its equivalent, to the quantity of heat, actual or latent, paid for its accomplishment.

In some cases it is not practicable to thus establish a numerical value of an efficiency; and it can only be shown that efficiency, in the sense of quantity of result compared with magnitude of means used, is increased or decreased by the operation of defined phenomena, or by conditions which can be specified. A common measure cannot always be found, or an exact law of relation established.

Increasing steam-pressure gives increasing economy up to a limit somewhere above customary pressures. The higher the pressure the greater the economic value of the steam in a steam-engine, but on the other hand the lower the efficiency of the boiler; and it is perfectly possible to reach a point at which the gain on the first score is more than counterbalanced by the loss on the second. Where the object sought is simply heating-power, the advantage lies, on the whole, on the side of low pressures.

235. The Measure of Efficiency of boilers is commonly a ratio of heat applied to a defined purpose or obtained in store, in a stated form, to the total quantity of heat from which it has been saved, another part having been diverted to other purposes, and, for the use considered, wasted. Thus, a given quantity of heat being stored as potential energy of chemical action in fuel, a small proportion of that energy is received at the steam-engine when that fuel is burned under a steam-boiler; the ratio of these two quantities—always a fraction and often small—is the *total* efficiency of the whole apparatus employed in the combustion of fuel, the transfer of heat-energy to the fluid in which it is stored, and its further transfer to the point at which it is usefully applied by transformation into mechanical energy and work.

236. The Efficiency of Combustion thus measures the ratio of the available heat-energy of the fuel to that set free by its union with oxygen, and is less than unity in the proportion in which the combustible portion of the fuel escapes such chemical change or is imperfectly burned, as when a part of the fuel falls into the ash-pit, is imbedded in clinker, or remains on the grate when the fire is extinguished; or as when carbon is only oxidized to carbon monoxide instead of being completely burned into dioxide. In well-managed furnaces the value of this efficiency approaches unity; it ought not to fall below 0.90, probably, in any ordinary case.

237. The Efficiency of Transfer of Heat similarly measures the ratio of heat received from the furnace by the boiler to that produced by combustion. That not transferred to the boiler is either sent up the chimney, where it is, in a certain degree, useful in producing draught, or it is lost by conduction and radiation to surrounding bodies. In good examples, the value of this ratio exceeds 0.75, and it should not usually fall under fifty or sixty per cent. Its best value depends on considerations, however, to be hereafter stated, and it is not always desirable that it should have the highest value possible, or approximate unity.

238. The Net Efficiency of Boiler is the continued product of all efficiencies of the several operations constituting the

process of production and supply of steam; and it can only be exactly known by direct experimental determination, either as a whole, or in detail, by the ascertainment of the values of each of its factors. It is this quantity with which the engineer and the proprietor are principally concerned, and the study of the elementary efficiencies is mainly useful in revealing the causes and the extent of wastes in the several steps of the whole process.

239. **The Finance of Efficiency** is a more important matter, if possible, than the theory of either or all the efficiencies already defined. It is obvious that, in any case in which steam is demanded at a given pressure and in stated quantity, it may be obtained either expensively by using ill-chosen types, construction, and proportion of boiler, and operating under unfortunate conditions, or economically by an opposite method. In general, the larger the boiler the less the cost of steam in fuel and operating expenses; the smaller the boiler the heavier the coal bills and related accounts. On the other hand, the larger boiler is of great first cost, expensive in its interest, insurance, and perhaps maintenance, accounts; while the opposite is true of the smaller boiler. It is equally evident that a boiler may be too large and costly for real and ultimate financial economy; or it may be too small and too wasteful of fuel to give best results as read on the final balance-sheet, at the end of its period of service. There must in every case be some proportion of size and cost to quantity of steam demanded which shall, on the whole, prove in the end a financial success, and give the work required of it at the least total cost.

240. **Commercial Efficiency** must thus be added as the final and most important of all efficiencies, as judged from the standpoint of the proprietor, and as measuring also the success of the designer of the steam-generating apparatus; and the following definitions and principles may be admitted as a basis for the mathematical theory of the finance of steam-boiler operation:

In the design and construction of a steam-boiler, and in its operation, problems arise which must be solved by the mechanical engineer in their natural order before he can say with

confidence that the best interests of the purchaser or proprietor of the apparatus are fully met in its construction and management. Such are the following:

(1) *The "Efficiency of the Steam-boiler"* is the ratio of the total quantity of heat utilized in the production of steam to that set free in the combustion of the fuel. It has as the maximum limit unity, and is a function of area of heating-surface, and of factors dependent upon the character of the fuel and its combustion, and upon the design of the boiler.

(2) *The "Commercial Efficiency"* or the *"Efficiency of Capital"* employed in the maintenance of steam-generating apparatus of a *given power* is measured by the ratio of quantity of steam produced to the total cost of its continuous production, i.e., by the reciprocal of the total cost of steam per pound or per cubic foot at the required pressure. This efficiency is a maximum when that cost is a minimum.

(3) *The "Efficiency of a Given Boiler Plant,"* as the Author has called it, or the commercial efficiency of a steam-boiler already in place and in operation, is still another quantity. It is a maximum when the work done by the boiler can be increased beyond that for which it was proportioned—if designed originally to give maximum efficiency of capital at a prearranged power, as above—until the amount of steam made by that boiler *per dollar of working expense* is made a maximum.

These three efficiencies differ essentially in their character, and are determined by different processes. In the first case, the engineer designing a boiler finds himself called upon to determine what is the maximum efficiency that it will be economical, or otherwise advisable, to endeavor to secure, and then calculates the proportions necessary to secure that efficiency. Or, knowing the proportions of any boiler already designed and built, he may be required to calculate its probable efficiency and the quantity of fuel required to make a certain quantity of steam, i.e., to estimate the quantity of steam which will be generated per pound of coal burned.

In the second case, the designing engineer calculates the proportions of heating-surface to grate-surface or to fuel burned. where the quantity of steam required is known, and the

conditions determining costs, which shall give that quantity of steam at least total running expense. The investigation determines how large a boiler or what extent of heating-surface will, all things considered, pay best.

In the third case, the boiler is in place and in operation, and it is found that it is advisable to ascertain what quantity of steam is made when the cost of that steam, per unit of weight or of volume, becomes a minimum.

In the first two cases, the variable element is usually the area of heating-surface per pound of fuel burned in the unit of time; in the last, the variable may be either the quantity of fuel burned or of steam made.

(4) *To what Capacity may any Given Boiler be forced without exceeding that Cost of Steam at which a Paying Profit is given?* is another problem in steam-boiler efficiency, and one which is of more frequent occurrence and is usually more important than the preceding.

The economical maximum of steam-production is evidently determined by the money value, to the producer, of the steam made.

241. Efficiency of the Steam Boiler.—This case has been studied by Rankine, who deduces a very simple and handy formula for the efficiency of a boiler of known proportions, using a fuel of known calorific value. (See § 98, p. 221.)

Taking the rate of conduction of heating-surfaces as varying as the square of the difference of temperatures of the gas and of the water on opposite sides of the sheet, the formula

$$E = \frac{1}{1 + \frac{ac'^2 W^2}{SH}}$$

is readily deduced, in which E is the efficiency, a a constant, c' the specific heat of the furnace-gases, and W their weight; while H is the total heat expended and S the heating-surface. This expression is further transformed into

$$E_1 = \frac{BE}{1 + \frac{AF}{S}},$$

in which E is the theoretical evaporative power of the fuel per pound, E_1 the probable actual evaporation in a boiler in which F is the weight of fuel burned on the unit of area of grate, and S is the area of heating-surface per unit of the same area.

A and B are here coefficients, having values respectively of 0.3 to 0.5 and 0.9 to 1 for bituminous coals, according to Rankine, and from 0.3 to 0.5 and from 0.8 to 0.9 with anthracite coal, as determined by experiments made by the Author. The lowest and best values of A are obtained when using a minimum needed air-supply, and the value of that coefficient is seen, by comparing the two equations just given, to vary as the square of the quantity of air supplied to the fuel. The value of B is dependent upon the character of the boiler, being greater as the design and construction are improved.

The following are illustrations of the results thus obtained:

EFFICIENCY OF STEAM-BOILERS.

$\frac{F}{S}$	I. $A = 0.5$; $B = 1$.	II. $A = 0.3$; $B = 1$.	III. $A = 0.5$; $B = 0.9$.	IV. $A = 0.3$; $B = 0.9$.
0.17	0.92	0.95	0.83	0.86
0.33	0.87	0.91	0.78	0.82
0.40	0.83	0.89	0.75	0.80
0.50	0.80	0.87	0.72	0.78
0.67	0.75	0.83	0.68	0.75

242. Commercial Efficiency of the Boiler.—The expenses of operating a steam-boiler may be classed under three heads:

(1) Those costs of boiler and its maintenance which are dependent upon the size and the character of the boiler itself and its attachments, such as interest on cost of boiler and setting, rent of building, and other items on construction account, such as taxes, insurance, repairs and depreciation, etc., etc.

(2) Those costs of operation which are dependent upon the quantity of steam made and of fuel consumed, such as market price of fuel, cost of transportation, storage (an important item on shipboard especially), and of feeding into the furnace, cost of feed-water and its introduction into the boiler, and often a certain part of other costs of attendance and supply.

(3) In addition to these variable expenses are often, perhaps usually, to be counted certain constant expenses which are un-

affected by any change of proportions of boiler likely to be made in the assumed case, such as nearly all, or frequently quite all, the costs of attendance.

A given amount of steam being demanded, it may be obtained either from a boiler so small as to use fuel extravagantly, or from a large boiler using fuel economically. In each case arising in practice, there will be found a certain easily determined proportion of heating-surface to grate-surface, and a definite size of boiler which will, on the whole, supply the desired quantity of steam most economically. Thus:

Let the total cost of fuel per annum and per pound burned per hour on the square foot of grate or on the square metre be called C. Let the total cost per annum of boiler, per square foot or per square metre of heating-surface, be called D, and let $\frac{C}{D} = R$. In the first item is included Class 1, and in the second Class 2.

Then the cost of boiler maintenance per annum is DSG, where S is the area of heating-surface per unit of area of grate and G is the area of grate. The cost of fuel, etc., per annum, as per Class 2, is CFG, if F is the weight of fuel burned per unit of area of grate.

The total of costs variable with change of proportion of boiler is

$$P = DSG + CFG.$$

The profitable work of the boiler is measured by the quantity, by weight, of steam made, $FGE_1 = W$; E_1 being the evaporation of water per unit of weight of fuel.

The ratio of cost to work done is

$$y = \frac{P}{W} = \frac{DGS + CFG}{FGE_1} = \frac{CF + DS}{E_1 F}.$$

This quantity being made a minimum by variation of the area S, the most economical boiler is obtained.

But E_1 is a function of S, and, taking the value of E_1 from the equation

$$E_1 = \frac{BE}{1 + \frac{AF}{S}},$$

we obtain

$$y = \frac{(DGS + CFG)\left(1 + \frac{AF}{S}\right)}{BEFG} = \frac{DGS + ADFG + CFG + \frac{ACF^2G}{S}}{BEFG}$$

$$= \frac{DS + ADF + CF + \frac{ACF^2}{S}}{BEF},$$

which is a minimum when

$$S_1 = F\sqrt{\frac{AC}{D}} = F\sqrt{AR};\ \frac{S_1}{F} = \sqrt{AR}.$$

In illustration: Let a boiler, set in place, complete with all its appurtenances and in running order, cost \$3 per square foot of heating-surface, and the annual charges on all accounts entered in Class 1, above, be 20 per cent on this cost, the annual charge becomes $DS = \$0.60 \times S$ per square foot of grate, i.e., $D = \$0.60$. Let the cost of operation, as for Class 2, amount to \$15 per annum per pound of fuel burned per hour on the square foot of grate; then $CF = \$15 \times F$; $C = \$15$; $\frac{C}{D} = R = 25$.

Assume $F = 10$ pounds of fuel per hour per square foot of grate, $A = 0.5$.

For this case, then, the boiler should have per square foot of grate,

$$S_1 = F\sqrt{AR} = 10 \times (0.5 \times 25)^{\frac{1}{2}} = 35;$$

35 square feet of heating-surface.

Similarly we get the following values:

COMMERCIAL EFFICIENCY OF BOILERS.

Ratio of Areas of Heating and Grate Surfaces.

Values of S.

F	6	10	12	15	20	30	40	50
R								
25	21	35	42	52	70	105	140	175
16	17	28	34	42	56	84	112	140
9	12	21	24	32	42	63	84	105
4	8	14	16	21	28	42	56	70

These values are 20 or 25 per cent lower for forced draught.

Where the boiler is worked almost continuously, as in flour-mills and some other establishments kept in operation night and day throughout the year, the higher values will be found correct; when the boiler is worked discontinuously or, as in steam fire-engines and some classes of steam-vessels, a comparatively small proportion of the annual working time of the establishment or whole plant, the values of S_1 become very small.

It is seen that the best area of heating-surface will vary nearly as the square root of the total working time per annum. Boilers worked continuously, worked twelve hours out of the twenty-four, and eight hours in the day, will require, respectively, values of S having the proportion 1, 0.7, and 0.6 nearly.

The total required area of grate is $\frac{W}{E_1F} = G$; the total area of heating-surface is $\frac{WS_1}{FE_1} = S_1G = \frac{W(S_1 + AF)}{BEF}$.

The following are examples, in greater detail, of the application of the above:

EXPENSE ON BOILER ACCOUNT AND MAXIMUM COMMERCIAL EFFICIENCY.

CASES.	STATIONARY.		MARINE.	
	I.	II.	III.	IV.
Class 1 (D)	Cornish.	Tubular.	Tubular.	Tubular.
Total annual cost of boiler per unit of S.....	\$1.50	\$2.00	\$3.00	\$2.00
Interest....................................	.09	.12	.15	.12
Repairs and depreciation....................	.15	.20	.45	.30
Rent, insurance, and miscellaneous..........	.10	.07	1.00	.20
Total value of D..................	.34	.38	1.60	.62
Class 2 (C).				
Fuel (@ \$5 for I., II., IV.; \$4 for III.) per unit of F....	7.50	7.20	12.00	2.00
Transportation and storage..................	1.00	1.00	10.00	1.00
Attendance (variable cost)..................	0.00	0.50	0.50	0.00
Total..............................	8.50	9.00	22.50	3.00
Value of $\frac{C}{D} = R$..................	25	23	14	5
Value of A......................	0.5	0.3	0.3	0.5
Value of $\sqrt{AR}$..................	3.5	2.7	2.0	1.6
Value of F......................	8	10	16	20
Value of $\sqrt{AR'} = S_1$..............	28	27	32	32

R varies in magnitude very greatly in practice, falling as low as 4 and rising as high as 50 with varying cost of fuel and length of working time.

The engineer thus solves this important problem in boiler-design which may be thus enunciated: To determine the commercial efficiency of a steam-boiler doing a fixed amount of work; or, given all variable expenses of boiler installation, maintenance, and operation, to determine what proportion of heating-surface to grate-surface, or to fuel burned, will give the required amount of power at least total cost.

243. Commercial Efficiency of a Fixed Plant.—A second commercial problem may sometimes be presented to the engineer: A steam-boiler is in place and in operation; all constant expenses are known and all variable costs of maintenance and operation are determinable. The question arises, or may arise whenever additional steam may be usefully employed: How much work can be obtained from the apparatus when driven to such an extent as to yield the maximum amount of steam per dollar of total cost of operation? The independent variable is now the quantity of fuel burned in the boiler, and this is, in the established equation, represented by F, the fuel burned per unit of area of grate. This problem is thus stated:

Given: All expenses, constant and variable, the method of variation of the latter, and the proportions of the boiler being given, to determine that rate of combustion which will make the commercial efficiency of the given plant a maximum.

For this case let K represent that total annual expense of working which is independent of Classes 1 and 2 and which falls into Class 3, and let $k = \frac{K}{G}$.

Let all other symbols stand as before.

Then the total cost of maintenance and operation will be

$$P' = kG + DGS + CFG,$$

while the work done will be, as before,

$$W = FGE_1.$$

The quantity to be made a minimum is, for the present case, the quotient of P' by W,

$$y = \frac{P'}{W} = \frac{k + DS + CF}{E_1 F},$$

F being taken as the independent variable.

This becomes a minimum when we substitute for E_1 its value $E_1 = \dfrac{BE}{1 + \dfrac{AF}{S}}$, and make the first derivative equal zero.

Then we find

$$F_1 = \sqrt{\frac{kS + DS^2}{AC}}.$$

When, in this expression for the value of F, giving maximum weight of steam for the dollar expended, we make $k = 0$, the expression may be reduced, as obviously should be possible, to the form shown already to be that giving the solution of the first problem:

$$S_1 = F\sqrt{AR}.$$

The following cases illustrate this problem:

EXPENSES OF BOILER AND MAXIMUM ECONOMY OF PLANT.

Cases.	Stationary. I.	Stationary. II.	Marine. III.	Marine. IV.
Cost of maintenance: D	\$0.34	\$0.58	\$0.88	\$0.62
Cost of operation: C	8.20	9.00	14.50	3.00
Cost of operation: K	30.00	25.00	10.50	10.00
For maximum fuel and work: F_1	16	13	17	21
For maximum efficiency, as before: F	8	10	16	20

Case No. 1 is that of a Cornish boiler, No. 2 that of a multitubular stationary boiler, No. 3 that of a sea-going steamer, and No. 4 that of a yacht.

It is seen that in all cases the weight of steam delivered from the boiler and the quantity of fuel burned at maximum commercial efficiency, for the case assumed, are less than where the boiler--once set and still capable of being forced to deliver

more steam than originally proposed and calculated upon—is worked up to a maximum delivery per dollar of total expense.

The figures above given should be found amply large. Water-tubular boilers have been known, frequently, to work, for years, steadily without repairs; and if well handled, all boilers should give low figures for such expense.

"Maximum commercial efficiency of boiler" and "Maximum efficiency of a given plant" are therefore by no means identical conditions; and it will usually be found that when this maximum work can be put on the boiler, it might be done still more economically by a boiler specially designed, as in the first problem, to do the increased quantity of work: the conclusion from this fact being simply that economy dictates that as much steam-power as possible should be grouped into a single plant in order to diminish the proportional cost of the constant part of running expenses, i.e., otherwise stated, there being given a certain necessary expenditure, invariable within certain limits with variation of size of boiler or of quantity of steam made, the larger the amount of work done without increasing this constant expense, the cheaper will the steam be made.

The larger the plant supervised by the engineer the less the total cost per pound of steam made, other conditions of economy being unchanged.

CHAPTER XIV.

STEAM-BOILER TRIALS.

244. The Object of a Trial of a Steam-boiler is to determine what is the quantity of steam that a boiler can supply under definitely prescribed conditions; what is the quality, as to moisture or dryness, of that steam; what is the amount of fuel demanded to produce that steam; what the character of the combustion, and the actual conditions of operation of the boiler when at work. The conditions prescribed for one trial may differ greatly from those of another trial, and such differences are often the essential matters to be studied. In any case it is assumed that the conditions under which the boiler is to be worked are to be definitely stated, and the engineer conducting the experiments is expected to ascertain all the facts which go to determine the performance of the boiler, and to state them with accuracy, conciseness, and completeness.

In the attempt to ascertain those facts the engineer meets with some difficulties, and finds it necessary to exercise the utmost care and skill. In conducting a steam-boiler trial the weight of the water supplied to the boiler must be determined; the weight of the fuel consumed must be obtained; the state of the steam made must be determined; and these quantities must all be noted at frequent intervals. It is also necessary to know whether the combustion is perfect or imperfect, and to what extent the conditions and facts noted are due to the boiler, and what to external conditions.

It has now come to be considered that the determination of power and economy of a steam-boiler demands all the care, skill, and perfection of method and of apparatus of any purely scientific investigation. It is essential that all work of this kind shall be done in substantially the same way, in order that comparisons may be made.

245. Tests of Value of Fuel are sometimes the sole object of a trial of a steam-boiler, the intent being to ascertain by actual experiment what quantity of water a fuel of unknown quality can evaporate in a boiler of which the general efficiency is fairly well established. In such cases the fuel is employed in the usual manner and the results compared with those obtained with fuels of known excellence. Thus, in a good type of boiler, having a good proportion of area of heating-surface to weight of fuel burned per hour, it may be found that a fuel of established reputation for uniform excellence will evaporate ten times its own weight of water "from and at" the boiling-point. The trial of a fuel of unknown quality may prove that this boiler will, under precisely similar conditions, evaporate an equal amount of water into steam, and yet the market price of the fuel may be considerably less than that of the other. The immediate result would be the substitution of the second for the first, should no counterbalancing disadvantages exist. In such cases the method of conducting the experiment is precisely the same as where the efficiency of the boiler is determined; but the object sought is quite a different one. This also commonly compels at least two trials, the one of the old and standard, the other of the new and uncertain fuel, and a comparison of boiler-efficiency as found in the two trials.

246. The Determination of the Value of a steam-boiler involves the measurement of its efficiency, independently of the nature of the fuel, and it is thus important that a standard system of measuring the effectiveness of the fuel should be settled upon, or that all variations of such effectiveness should be eliminated. The latter is commonly the course taken; and the determination of the efficiency of the boiler is based upon the measurement of the evaporation of water, under stated standard conditions, per unit weight of the combustible and burned portion of the fuel supplied during the trial.

But the power of the boiler is as important an element of its value as its efficiency, and a complete trial includes, usually, measurements of efficiency at both the rated and the maximum working power of the boiler as operated for its special purpose.

247. The Evaporative Power of Fuels depends upon

not only their chemical composition as fuels, but also to an important extent upon their structure and their physical condition in every aspect; on their greater or less purity, and the admixture of earths, moisture, or other foreign matters; the fitness of the furnace for their utilization; the air-supply; its quantity, temperature, and humidity; the proximity of chilling surfaces; the extent of the combustion-chamber in which the gases rising from the bed of coal or other combustible may be more or less completely consumed; and many other minor conditions, all of which tell, in a more or less important degree, upon their value and the efficiency of the system of heat-generation.

248. **Analyses of Fuels** are sometimes made, either as a check upon the results of the trial or in substitution for it. Should analysis show that a given fuel is rich in heat-producing elements, while trial fails to give the results that should have been obtained, and such as the use of other fuels in the same boilers indicates to be possible, it will at once appear that the fuel demands peculiar treatment, or some other arrangement of furnace. Should doubt exist which of a number of fuels of the same class is best, chemical analysis may give a quicker and cheaper answer to the question than a formal trial. It rarely happens, however, that any system is as satisfactory, in the end, as actual trial extending over so long a period as to eliminate uncertainties.

Methods of analysis differ somewhat. The following is a standard method of general treatment as prescribed by the Union of Engineers of Germany:*

In order to take a sample of the fuel, a shovelful from each barrow or wagon will be thrown into a box with a cover. The coal will be mixed up and spread in the form of a square upon a level floor, and then divided by two diagonals into four parts. Of these, two opposite parts will be taken away, the other two will be broken up small and mixed together. Another shovelful will then be thrown in, and the method continued until about 10 kilogrammes are in the box. This will then be

* *American Engineer*, August, 1883.

closed and reserved for chemical analysis. For accurate experiments the halves which have been taken away should also be analyzed.

To determine the moisture in the coal, about 10 grammes from the above-named sample is to be heated for two hours to 105° or 110° C. The loss in weight shows the moisture in the coal. Coal which happens to have been wetted by rain or otherwise should not be used. The test should be applied to coal in the average state of moisture at which it is delivered from the pit mouth, and this state should, if necessary, be determined beforehand. The remainder of the sample, powdered and mixed thoroughly, serves to determine the ash, the carbon, the hydrogen, the nitrogen, and the sulphur. The heating-value of the coal is determined as follows: Suppose that it is found to contain c per cent of carbon, h per cent of hydrogen, s per cent of sulphur, o per cent of oxygen, and w per cent of water, then the theoretical heating-value is given by the formula of Dulong as follows:

(*a*). *Referred to Water at* 0° *Cent.*

$$8100c + 34320\left(h - \frac{o}{8}\right) + 2500s.$$

(*b*). *Referred to Water at* 100° *Cent.*

$$8100c + 34200\left(h - \frac{o}{8}\right) + 2500s - 636.5\,(9h + w.)$$

To determine the quantity of air required for burning coal we have the following: One kilogramme of coal requires to burn it,

$$\frac{2.667c + 8h + s - o}{100 \times 1.43} \text{ cu. metres of oxygen; or,}$$

$$\frac{2.667c + 8h + s - o}{21 \times 1.43} \text{ cu. metres of air containing 21 per ct. of oxygen.}$$

The analyses should be made with care, by a skilled and experienced chemist, if any important question is to be settled.

249. **Economy of Fuel** is nearly synonymous with efficiency of boiler, as a matter of engineering simply; but when the finance of the case is studied, it is often found, from that

point of view, a very different mattter. It is perfectly possible to adopt so great a proportion of heating-surface, so large a boiler, that the gain in fuel saved, as compared with boilers of similar type and usual proportions, may be more than offset by the increased charges on account of enlargement of boiler. The efficiency of boiler, in the ordinary sense in which that term is used, is, however, a measure of economy. The variation of efficiency and of economy in fuel consumption is a function of the proportion of area and of heating-surface to fuel burned, and the object of a boiler-trial is to ascertain these relations with precision. An understanding should be had before the trial in regard to the kind of fuel to be used; where no reason of controlling importance exists to the contrary, the best obtainable coal should be selected, for the reason that a boiler can be better judged, and the results of its trial may be more satisfactorily compared with similar trials of other boilers, when the very best work of which it is capable is done by it. The differences between separate lots of the best coals are less than the differences between separate lots of inferior fuels, and the comparison is thus less difficult where the former are used.

The results of a boiler-trial at Cassel are reported to have given the following distribution of heat:*

	B. T. U.	per cent.
Heat of 1 lb. coal utilized	11,498.4	80.34
Carried off by gases	1,031.4	7.21
" " " brickwork	286.2	2.00
" " " ashes	234 0	1.63
" " " radiation, etc.	1,261.8	8.82
	14,311.8	100.00

The coal contained:

C	82.51	per cent.
H	4.73	" "
O	4.68	" "
H_2O	1.38	" "
Ash and Waste	6.70	" "
	100.00	

* Abstracts of Papers, XC., 1887, p. 70, Inst. C. E.

The data of the trial were:

Steam pressure (atmos.)	6.36
Water evap. per hr., lbs	4.501.79
" " " sq. ft. H. S. per hr., lbs	2.99
" " " lb. coal, lbs	10.50
Temp. feed-water in tank (Fahr.)	64°.4
" " " from heater	115°.52
" air in boiler-house	69°.8
" gas leaving flues	345°.2
Ratio air to theoretical quantity	1.31
Coal per sq. ft. G. S. per hr., lbs	14.67
" " " " H. S. " " "	0.297

250. **The Relative Values of Boilers** depend not only on their efficiencies, but also on their capacities for furnishing steam, and on various other qualities and attributes: as their greater or less complication in structure; their safety and durability; their volume, weight, and cost. The boiler-trial only settles questions relating to their efficiency and capacity, and their real relations of value, only just so far as those elements enter the problem. These are usually, however, the main factors, and their measurement by a test-trial gives the means of deciding, in nearly all cases, every question likely to present itself in the use of the apparatus.

251. **Variations of Efficiency** occur with variations in grate-area, in rate of combustion and in kind of fuel. In any given boiler, within a wide range of which the limits are usually far outside of practical conditions, the greater the quantity of fuel burned the less the amount of steam made per unit weight of that fuel; the smaller the quantity of fuel, burned under proper conditions, in the boiler, the higher the efficiency; and it has been seen in an earlier chapter, that the gain in efficiency, with increasing proportion of heating to grate surface or to fuel burned, is less and less as this increase goes on. By enlarging or reducing the grate, or by increasing or diminishing the draught and air-supply, and during a succession of trials, noting the method of variation of efficiency and of capacity for making steam, the law of such variations

may be established, and the best arrangement, all things considered, may be determined.

252. **Variations of Proportions** in different boilers, otherwise similar, have been seen to be capable of expression by a very simple algebraic expresssion on which all theories of efficiency are based. But in some cases this law is not found to be precisely applicable, and only test-trials of boilers so differing can be relied upon to give correct relations. The general relations already stated invariably hold; but it often happens that a steam-boiler exhibits peculiarities which make that exact statement inapplicable. It is not uncommon not only to compare actual performance, as shown by trial, with the results indicated by the theory, but also to alter the ratio of heating to grate surface by bricking over more or less of the grate, and by this or other expedients so varying that ratio in successive trials as to obtain an empirical and approximately exact expression for the law of variation of efficiency for the particular case in hand.

253. **Combined Power and Efficiency** distinguish the best types of boiler. That which, at a given cost, exhibits highest steam-producing power combined with greatest efficiency, is the best boiler. These qualities, however, are not usually compatible, and increased steam-production from any boiler is commonly attended with a decrease in efficiency; and as the one or the other of these qualities is the more important, the combination which will give best total result will vary. In no two cases will the same combination be equally desirable. Every boiler must be tested for both before it can be said whether it is satisfactorily adapted to its place and work.

254. **The Apparatus and Methods** of test-trials should be prescribed in the preliminary arrangements for every trial, and if possible should be in exact accordance with some accepted standard rules. The apparatus consists of scales and tanks for measurement of weights of coal and of water; gauges to give the pressure of steam; thermometers of great accuracy to determine the temperatures of water, steam, and flue-gases; and calorimeters to determine the quality of the steam and

the extent of superheating, or the percentage of moisture entrained by it.

The establishment of the correctness of this apparatus is the first of the preliminaries to their use. The standardization of the instruments is a matter of supreme importance, since upon their accuracy the whole work of the engineer is dependent. It is also a work demanding, in most cases, unusual skill and care, and, to be satisfactory, must generally be performed either at the manufacturer's, or at the office of the engineer conducting the trial. The scales can usually be standardized by the official sealer of weights and measures, and sealed by him ; the water-meters, if used, can be readily tested by the use of the scales so sealed ; the thermometers are, as a rule, best tested by their makers, and should be sent to the maker for test immediately before and directly after the test. The engineer often has a carefully preserved standard with which they may be compared in his own office. The same remarks apply to the examination of the gauges used, which should be standardized both before and after their use. The apparatus used in connection with the calorimeter, in the determination of the quality of the steam made, demand exceptional care in this process. Where it is unavoidable, the use of coarsely graduated thermometers and roughly constructed scales may be permitted, but only then when a very large number of observations are taken, and an average thus obtained which may befairly expected to fall within reasonable limits of error.

The method of starting and of stopping the trial is a very important matter, and one upon which engineers of experience and acknowledged authority are not in complete accord. The principles to be adhered to in this matter, as in every other detail of the operation of testing a boiler, are easily specified, but they are not always as easy of practice. All conditions should be as exactly the same at the beginning and at the end of the test as they can possibly be made. The period of the trial and the times of stopping and of starting should be capable of being exactly fixed, and the method of test should be

such as should permit of the commencement and the end occurring at these exactly defined times, or, as an alternative, they should be such that the work done by the boiler during the less precisely determinable time of beginning and ending of the trial should be as nearly as possible *nil*, so that a slight error as to time may not appreciably affect the results.

During the trial, provision should be made for the preservation of the utmost possible uniformity of working conditions throughout the whole period of the trial. Every irregularity gives rise to more or less loss of efficiency, and to uncertainty in regard to the correctness of the reported figures. The nearer the working of the boiler is kept to the final average for the trial, the better.

Uniformity of operation and maximum efficiency are best attainable during a trial when a system of record is adopted which allows of that regularity being shown at all times; and records in proper form are the best possible security against error of observation. Graphical methods should be adopted wherever practicable. Such methods of record exhibit most satisfactorily the accordance with or the deviation from the uniformity of operation considered so desirable on the score of efficiency and accuracy.

255. **Standard Test-trials** are made under established systems, and in accordance with codes of regulations which are accepted as representing a satisfactory system of procedure. In such cases the first step is to settle upon a standard of measurement and comparison that may be accepted by all who may be interested in the result. The standard nominal horse-power has already been described as now accepted by the best authorities.

The Committee of Judges of the Centennial Exhibition, to whom the trials of competing boilers at that exhibition were intrusted, adopted the unit, 30 *pounds of water evaporated into dry steam per hour from feed-water at* 100° *Fahrenheit, and under a pressure of seventy pounds per square inch above the atmosphere*, these conditions being considered to represent fairly

average practice. The quantity of heat demanded to evaporate a pound of water under these conditions is 1110.2 British thermal units, or 1.1496 "units of evaporation." The unit of power proposed is thus equivalent to the development of 33,305 heat-units per hour, or 34.488 units of evaporation. The "unit of evaporation" is taken as a certain weight—preferably unity of water, evaporated "from and at" the boiling-point under atmospheric pressure. The now-accepted unit of boiler-power, in the code constructed for the American Society of Mechanical Engineers,* is the equivalent of the Centennial Standard, and in all standard trials the commercial horse-power is taken as *an evaporation of* 30 *pounds of water per hour from a feed-water temperature of* 100° *Fahr. into steam at* 70 *pounds gauge-pressure*, which is equal to 34½ units of evaporation, that is, to 34½ pounds of water evaporated from a feed-water temperature of 212° Fahr. into steam at the same temperature. This standard is equal to 33,305 thermal units per hour.†

A boiler rated at any stated horse-power should be capable of developing that power with easy firing, moderate draught and ordinary fuel, while exhibiting good economy; and the boiler should be capable of developing one half or one third more than its rated power to meet emergencies at times when maximum economy is not the most important object to be attained.

256. Instructions and Rules governing the standard system of boiler-trial, prepared by a committee of the American Society of Mechanical Engineers, may be taken as a good illustration of such regulations as, in one form or another, have been customarily agreed upon by engineers conducting such work. They are (Thurston's Engine and Boiler Trials):

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* Transactions, vol. vi., 1884.

† An evaporation of 30 pounds of water from 100° F. into steam at 70 pounds pressure is equal to an evaporation of 34.488 pounds from and at 212°; and an evaporation of 34½ pounds from and at 212° F. is equal to 30.010 pounds from 100° F., into steam at 70 pounds pressure.

The "unit of evaporation" being equal to 965.7 thermal units, the commercial horse-power is 34.488 × 965.7 = 33.305 thermal units.

PRELIMINARIES TO A TEST.

I. *In preparing for* and conducting trials of steam-boilers, the specific object of the proposed trial should be clearly defined and steadily kept in view.

II. *Measure and record the dimensions,* position, etc., of grate and heating surfaces, flues and chimneys, proportion of air-space in the grate-surface, kind of draught, natural or forced.

III. *Put the Boiler in good condition.*—Have heating-surface clean inside and out, grate-bars and sides of furnace free from clinkers, dust and ashes removed from back connections, leaks in masonry stopped, and all obstructions to draught removed. See that the damper will open to full extent, and that it may be closed when desired. Test for leaks in masonry by firing a little smoky fuel and immediately closing damper. The smoke will then escape through the leaks.

IV. *Have an understanding with the parties* in whose interest the test is to be made as to the character of the coal to be used. The coal must be dry, or, if wet, a sample must be dried carefully and a determination of the amount of moisture in the coal made, and the calculation of the results of the test corrected accordingly.

Wherever possible, the test should be made with standard coal of a known quality. For that portion of the country east of the Alleghany Mountains good anthracite egg coal or Cumberland semi-bituminous coal may be taken as the standard for making tests. West of the Alleghany Mountains and east of the Missouri River, Pittsburg lump coal may be used.*

V. *In all important tests* a sample of coal should be selected for chemical analysis.

VI. *Establish the correctness of all apparatus* used in the test for weighing and measuring. These are:

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* These coals are selected because they are almost the only coals which contain the essentials of excellence of quality, adaptability to various kinds of furnaces, grates, boilers, and methods of firing, and wide distribution and general accessibility in the markets.

1. Scales for weighing coal, ashes, and water.

2. Tanks, or water-meters for measuring water. Water-meters, as a rule, should only be used as a check on other measurements. For accurate work, the water should be weighed or measured in a tank.

3. Thermometers and pyrometers for taking temperatures of air, steam, feed-water, waste gases, etc.

4. Pressure-gauges, draught-gauges, etc.

VII. *Before beginning a test*, the boiler and chimney should be thoroughly heated to their usual working temperature. If the boiler is new, it should be in continuous use at least a week before testing, so as to dry the mortar thoroughly and heat the walls.

VIII. Before beginning a test, the boiler and connections should be free from leaks, and all water-connections, including blow and extra-feed pipes, should be disconnected or stopped with blank flanges, except the particular pipe through which water is to be fed to the boiler during the trial. In locations where the reliability of the power is so important that an extra feed-pipe must be kept in position, and in general when for any other reason water-pipes other than the feed-pipes cannot be disconnected, such pipes may be drilled so as to leave openings in their lower sides, which should be kept open throughout the test as a means of detecting leaks, or accidental or unauthorized opening of valves. During the test the blow-off pipe should remain exposed.

If an injector is used, it must receive steam directly from the boiler being tested, and not from a steam-pipe, or from any other boiler.

See that the steam-pipe is so arranged that water of condensation cannot run back into the boiler. If the steam-pipe has such an inclination that the water of condensation from any portion of the steam-pipe system may run back into the boiler, it must be trapped so as to prevent this water getting into the boiler without being measured.

STARTING AND STOPPING A TEST.

A test should last at least ten hours of continuous running, and twenty-four hours whenever practicable. The conditions of the boiler and furnace in all respects should be, as nearly as possible, the same at the end as at the beginning of the test. The steam-pressure should be the same, the water-level the same, the fire upon the grates should be the same in quantity and condition, and the walls, flues, etc., should be of the same temperature. To secure as near an approximation to exact uniformity as possible in conditions of the fire and in temperatures of the walls and flues, the following method of starting and stopping a test should be adopted:

X. *Standard Method.*—Steam being raised to the working pressure, remove rapidly all the fire from the grate, close the damper, clean the ash-pit, and as quickly as possible start a new fire with weighed wood and coal, noting the time of starting the test and the height of the water-level while the water is in a quiescent state, just before lighting the fire.

At the end of the test, remove the whole fire, clean the grates and ash-pit, and note the water-level when the water is in a quiescent state; record the time of hauling the fire as the end of the test. The water-level should be as nearly as possible the same as at the beginning of the test. If it is not the same, a correction should be made by computation, and not by operating pump after test is completed. It will generally be necessary to regulate the discharge of steam from the boiler tested by means of the stop-valve for a time while fires are being hauled at the beginning and at the end of the test, in order to keep the steam-pressure in the boiler at those times up to the average during the test.

XI. *Alternate Method.*—Instead of the Standard Method above described, the following may be employed where local conditions render it necessary:

At the regular time for slicing and cleaning fires have them burned rather low, as is usual before cleaning, and then thoroughly cleaned; note the amount of coal left on the grate as nearly as it can be estimated; note the pressure of

steam and the height of the water-level—which should be at the medium height to be carried throughout the test—at the same time; and note this time as the time of starting the test. Fresh coal, which has been weighed, should now be fired. The ash-pits should be thoroughly cleaned at once after starting. Before the end of the test the fires should be burned low, just as before the start, and the fires cleaned in such a manner as to leave the same amount of fire, and in the same condition, on the grates as at the start. The water-level and steam-pressure should be brought to the same point as at the start, and the time of the ending of the test should be noted just before fresh coal is fired.

DURING THE TEST.

XII. *Keep the Conditions Uniform.*—The boiler should be run continuously, without stopping for meal-times or for rise or fall of pressure of steam due to change of demand for steam. The draught being adjusted to the rate of evaporation or combustion desired before the test is begun, it should be retained constant during the test by means of the damper.

If the boiler is not connected to the same steam-pipe with other boilers, an extra outlet for steam with valve in same should be provided, so that in case the pressure should rise to that at which the safety-valve is set, it may be reduced to the desired point by opening the extra outlet, without checking the fires.

If the boiler is connected to a main steam-pipe with other boilers, the safety-valve on the boiler being tested should be set a few pounds higher than those of the other boilers, so that in case of a rise in pressure the other boilers may blow off, and the pressure be reduced by closing their dampers, allowing the damper of the boiler being tested to remain open, and firing as usual.

All the conditions should be kept as nearly uniform as possible, such as force of draught, pressure of steam, and height of water. The time of cleaning the fires will depend upon the character of the fuel, the rapidity of combustion, and the kind of grates. When very good coal is used, and the combustion not too rapid, a ten-hour test may be run without any cleaning

of the grates, other than just before the beginning and just before the end of the test. But in case the grates have to be cleaned during the test, the intervals between one cleaning and another should be uniform.

XIII. *Keeping the Records.*—The coal should be weighed and delivered to the firemen in equal portions, each sufficient for about one hour's run, and a fresh portion should not be delivered until the previous one has all been fired. The time required to consume each portion should be noted, the time being recorded at the instant of firing the first of each new portion. It is desirable that at the same time the amount of water fed into the boiler should be accurately noted and recorded, including the height of the water in the boiler, and the average pressure of steam and temperature of feed during the time. By thus recording the amount of water evaporated by successive portions of coal, the record of the test may be divided into several divisions, if desired, at the end of the test, to discover the degree of uniformity of combustion, evaporation, and economy at different stages of the test.

XIV. *Priming Tests.*—In all tests in which accuracy of results is important, calorimeter tests should be made of the percentage of moisture in the steam, or of the degree of superheating. At least ten such tests should be made during the trial of the boiler, or so many as to reduce the probable average error to less than one per cent, and the final records of the boiler test corrected according to the average results of the calorimeter tests.

On account of the difficulty of securing accuracy in these tests the greatest care should be taken in the measurements of weights and temperatures. The thermometers should be accurate to within a tenth of a degree, and the scales on which the water is weighed to within one hundredth of a pound.

ANALYSES OF GASES.—MEASUREMENT OF AIR-SUPPLY, ETC.

XV. In tests for purposes of scientific research, in which the determination of all the variables entering into the test is desired, certain observations should be made which are in general not necessary in tests for commercial purposes. These are the measurement of the air-supply, the determination of its con-

tained moisture, the measurement and analysis of the flue-gases, the determination of the amount of heat lost by radiation, of the amount of infiltration of air through the setting, the direct determination by calorimeter experiments of the absolute heating value of the fuel, and (by condensation of all the steam made by the boiler) of the total heat imparted to the water.

The analysis of the flue-gases is an especially valuable method of determining the relative value of different methods of firing, or of different kinds of furnaces. In making these analyses great care should be taken to procure average samples, since the composition is apt to vary at different points of the flue, and the analyses should be intrusted only to a thoroughly competent chemist, who is provided with complete and accurate apparatus.

As the determination of the other variables mentioned above are not likely to be undertaken except by engineers of high scientific attainments, and as apparatus for making them is likely to be improved in the course of scientific research, it is not deemed advisable to include in this code any specific directions for making them.

RECORD OF THE TEST.

XVI. A "log" of the test should be kept on properly prepared blanks, containing headings as follows:

Time.	Pressures.			Temperatures.					Fuel.		Feed-water.	
	Barometer.	Steam-gauge.	Draught-gauge.	External Air.	Boiler-room.	Flue.	Feed-water.	Steam.	Time.	Pounds.	Time.	Pounds or c. ft.

REPORTING THE TRIAL.

XVII. The final results should be recorded upon a properly prepared blank, and should include as many of the following items as are adapted for the specific object for which the trial is made. The items marked with a * may be omitted for ordinary trials, but are desirable for comparison with similar data from other sources.

Results of the trials of a..................................
Boiler at..
To determine..

1. Date of trial.............................			
2. Duration of trial.........................	hours.		
DIMENSIONS AND PROPORTIONS.			
Leave space for complete description. See Appendix XXIII.			
3. Grate-surface.... wide....long....Area....	sq. ft.		
4. Water-heating surface.....................	sq. ft.		
5. Superheating-surface......................	sq. ft.		
6. Ratio of water heating surface to grate-surface..................................			
AVERAGE PRESSURES.			
7. Steam-pressure in boiler, by gauge........	lbs.		
*8. Absolute steam-pressure	lbs.		
*9. Atmospheric pressure, per barometer.......	in.		
10. Force of draught in inches of water........	in.		
AVERAGE TEMPERATURES.			
*11. Of external air..........................	deg.		
*12. Of fire-room.............................	deg.		
*13. Of steam.................................	deg.		
14. Of escaping gases.........................	deg.		
15. Of feed-water.............................	deg.		
FUEL.			
16. Total amount of coal consumed †..........	lbs.		
17. Moisture in coal..........................	per cent.		
18. Dry coal consumed.........................	lbs.		
19. Total refuse, dry......pounds =...........	per cent.		
20. Total combustible (dry weight of coal, Item 18, less refuse, Item 19)................	lbs.		
*21. Dry coal consumed per hour...............	lbs.		
*22. Combustible consumed per hour............	lbs.		

* See reference in paragraph preceding table.

† Including equivalent of wood used in lighting fire. 1 pound of wood equals 0.4 pound coal. Not including unburnt coal withdrawn from fire at end of test.

RESULTS OF CALORIMETRIC TESTS.			
23. Quality of steam, dry steam being taken as unity..................................			
24. Percentage of moisture in steam...........	per cent.		
25. Number of degrees superheated......	deg.		
WATER.			
26. Total weight of water pumped into boiler and apparently evaporated *.............	lbs.		
27. Water actually evaporated, corrected for quality of steam †......................	lbs.		
28. Equivalent water evaporated into dry steam from and at 212° F.†....................	lbs.		
*29. Equivalent total heat derived from fuel in British thermal units †....................	B. T. U.		
30. Equivalent water evaporated into dry steam from and at 212° F. per hour............	lbs.		
ECONOMIC EVAPORATION.			
31. Water actually evaporated per pound of dry coal, from actual pressure and temperature †	lbs.		
32. Equivalent water evaporated per pound of dry coal from and at 212° F.†...........	lbs.		
33. Equivalent water evaporated per pound of combustible from and at 212° F.†.	lbs.		

* Corrected for inequality of water-level and of steam-pressure at beginning and end of test.

† The following shows how some of the items in the above table are derived from others:

Item 27 = Item 26 × Item 23.

Item 28 = Item 27 × Factor of evaporation.

Factor of evaporation $= \dfrac{H - h}{965.7}$, H and h being respectively the total heat-units in steam of the average observed pressure and in water of the average observed temperature of feed, as obtained from tables of the properties of steam and water.

Item 29 = Item 27 × $(H - h)$.

Item 31 = Item 27 ÷ Item 18.

Item 32 = Item 28 ÷ Item 18 or = Item 31 × Factor of evaporation.

Item 33 = Item 28 ÷ Item 20 or = Item 32 ÷ (per cent 100 − Item 19).

Items 36 to 38. First term = Item 20 $\times \dfrac{6}{5}$

Items 40 to 42. First term = Item 39 × 0.8698.

Item 43 = Item 29 × 0.00003 or $= \dfrac{\text{Item 30}}{34\frac{1}{2}}$.

Item 45 $= \dfrac{\text{Difference of Items 43 and 44}}{\text{Item 44}}$.

COMMERCIAL EVAPORATION.			
34. Equivalent water evaporated per pound of dry coal with one sixth refuse, at 70 pounds gauge-pressure, from temperature of 100° F. = Item 33 multiplied by 0.7249	lbs.		
RATE OF COMBUSTION.			
35. Dry coal actually burned per square foot of grate-surface per hour....................	lbs.		
*36. Consumption of dry coal per hour. Coal assumed with one sixth refuse.† — Per sq. ft. of grate-surface...........	lbs.		
*37. Consumption of dry coal per hour. Coal assumed with one sixth refuse.† — Per sq. ft. of water-heating surface....	lbs.		
*38. Consumption of dry coal per hour. Coal assumed with one sixth refuse.† — Per sq. ft. of least area for draught...	lbs.		
RATE OF EVAPORATION.			
39. Water evaporated from and at 212° F. per square foot of heating-surface per hour...	lbs.		
*40. Water evaporated per hour from temperature of 100° F. into steam of 70 pounds gauge-pressure.† — Per sq. ft. of grate-surface..........	lbs.		
*41. Water evaporated per hour from temperature of 100° F. into steam of 70 pounds gauge-pressure.† — Per sq. ft. of water-heating surface..	lbs.		
*42. Water evaporated per hour from temperature of 100° F. into steam of 70 pounds gauge-pressure.† — Per sq. ft. of least area for draught.	lbs.		
COMMERCIAL HORSE-POWER.			
43. On basis of thirty pounds of water per hour evaporated from temperature of 100° F. into steam of 70 pounds gauge pressure, (= $34\frac{1}{2}$ lbs. from and at 212°)†.........	H. P.		
44. Horse-power, builders' rating, at.....square feet per horse-power.....................	H. P.		
45. Per cent developed above, or below, rating†..................................	Per cent.		

257. **Precautions** are to be taken in every possible way to prevent and avoid irregularities in the conduct of the trial and errors of observation.*

In preparing for and conducting trials of steam-boilers the specific object of the proposed trial should be clearly defined and steadily kept in view, and as suggested by Mr. Hoadley—

(1) If it be to determine the efficiency of a given style of boiler or of boiler-setting under normal conditions, the boiler brickwork, grates, dampers, flues, pipes, in short, the whole apparatus, should be carefully examined and accurately described,

* The appendix to the report above quoted should be read in this connection.

and any variation from a normal condition should be remedied, if possible, and if irremediable, clearly described and pointed out.

(2) If it be to ascertain the condition of a given boiler or set of boilers with a view to the improvement of whatever may be faulty, the conditions actually existing should be accurately observed and clearly described.

(3) If the object be to determine the relative value of two or more kinds of coal, or the actual value of any kind, exact equality of conditions should be maintained if possible, or, where that is not practicable, all variations should be duly allowed for.

(4) Only one variable should be allowed to enter into the problem; or, since the entire exclusion of disturbing variations cannot usually be effected, they should be kept as closely as possible within narrow limits, and allowed for with all possible accuracy.

Blanks should be provided in advance, in which to enter all data observed during the test. The preceding instructions contain the form used in presenting the general results. Records should be, as far as possible, made in a standard form, in order that all may be comparable.

The observations must be made by the engineer conducting the trial, or by his assistants, with this object distinctly in mind; and each should have a well-defined part of the work assigned him, and should assume responsibility for that part, having a distinct understanding in regard to the extent of his responsibility, and a good idea of the extent and nature of the work done by his colleagues, and the relations of each part to his own. No observations should be permitted to be made by unauthorized persons for entrance upon the log; and no duties should be permitted to be delegated by one assistant to another, without consultation and distinct understanding with the engineer in charge. The trial should, wherever possible, be so conducted that any error that may occur in the record may be detected, checked, or, if advisable, removed, by some process of mutual verification of related observations. It is in this direction that the use of graphical methods of record and automatic instruments have greatest value.

Several methods of weighing fuel have been found very satisfactory, but it should be an essential feature that the weights shall be made by one observer and checked by another, at as distant a point as is convenient. The weighing of the fuel by one observer at the point of storage, and the record at that point of times of delivery, as well as of weights of each lot, and the tallying of the number and record of the time of receipt at the furnace-door, will be usually found a safe system. The failure to record any one weight leads to similar error, and can only be certainly prevented by an effective method of double observation and check.

The same remarks apply, to a considerable extent, to the weighing of the water fed to the boiler. A careful arrangement of weighing apparatus, a double set of observations, where possible, and thus safe checks on the figures obtained, are essential to certainty of results. With good observers at the tank, and with small demand for water, a single tank can be used; but two are preferable in all cases, and three should be used if the work demands very large amounts of feed-water, as at trials of very large boilers, or of "batteries." The more uniform the water-supply, as well as the more steady the firing, the less the liability to mistake in making the record.

The two blanks which follow were prepared by the Author for use in laboratory as well as professional work.

258. The Results of Trials actually conducted under acceptable conditions, and with all the precautions which have been advised, are illustrated by the following examples:

The first case was a trial which was carried out in accordance with the above programme. The measurements of the feed-water were made by passing the water through a Worthington metre into two wooden tanks located on Fairbanks Standard Platform Scales. The pipe connections were so arranged that one tank could be filled and weighed while the other tank was being emptied into the boiler.

Each tank was filled once every half hour. As soon as the tank was full and the pumping into the boiler commenced, the temperature of the feed-water was taken by sensitive thermometers reading to one-tenth of a degree.

TABLE I.

LOG OF TRIAL BY MECHANICAL LABORATORY, DEPARTMENT OF ENGINEERING.

Test made at ____________________

____

on ____________________

$$x = \frac{U - wh}{H - h}$$

$$\frac{\frac{U}{w} + t - T}{0.48} = \text{Degrees of Superheating.}$$

Time.	Pressures.			Temperatures.					Weights.			Remarks.
	Barometer.	Steam-gauge	Draught-gauge.	External Air.	Boiler-room.	Fuel.	Feed-water.	Steam.	Fuel.	Feed-water.		
										Per Metre.	Per Tank.	

PRIMING TESTS.

No.	Time.	Steam-pressures.	Calorimeter.					Heat-units per Pound from Boiler.		Heat transferred to Calorimeter. $W \times R = U$	Heat from Steam $H = T - t'$	Heat from Water $h = t - t'$	Steam run into Calorimeter. x	Percentage of Priming. y	Superheating.		Remarks.
			Weights.		Temperature.												
			Condensing Water. W	Wet Steam. w	Initial. t''	Final t'	Range. $R = t' - t''$	Water. t	Steam. T						Degrees.	Heat-units.	

TABLE II.

AVERAGE AND TOTAL RESULTS OF TRIAL, MECHANICAL LABORATORY, DEPARTMENT OF ENGINEERING.

Trial made at________________ Fuel________________

on________________ Composition________________

Number of Trial.	Date of Trial.	Length of Trial.	Areas.				Ratio of Grate to Heating-surface.	Average Temperatures.				Average Pressures.			Consumption of Fuel.			Ashes.		Total Combustible.	Remarks.
			Grate.	Heating-surface.	Super-heating-surface.	Least Cross-section of Flues.		Boiler-room.	External Air.	Entrance to Chimney.	Feed-water.	Barometer.	Steam-gauge.	Draught-gauge.	Total.	Per square foot of Grate per hour.	Per sq. ft. of Heating-surface per hour.	Total.	Proportion of Total Fuel.		
		Hours.	sq. ft.	sq. ft.	sq. ft.	sq. ft.		Fahr.	Fahr.	Fahr.	Fahr.	ins.	lbs.	ins.	lbs.	lbs.	lbs.	lbs.	per ct.	lbs.	

Apparent Evaporation.									Real Evaporation.											
Per Pound of Fuel.			Per Pound of Combustible.			Per Square Foot of Heating-surface, per Hour.			Per Pound of Fuel.			Per Pound of Combustible.			Per Square Foot of Heating-surface, per Hour.			Square feet of Heating-surface required to Evaporate one Cubic Foot of Water.		
From actual temperature of feed-water and at actual steam-pressure.	Equivalent from and at 212° F.	Equivalent from 212° F. and at actual steam-pressure.	From actual temperature of feed-water and at actual steam-pressure.	Equivalent from and at 212° F.	Equivalent from 212° F. and at actual steam-pressure.	From actual temperature of feed-water and at actual steam-pressure.	Equivalent from and at 212° F.	Equivalent from 212° F. and at actual steam-pressure.	From actual temperature of feed-water and at actual steam-pressure.	Equivalent from and at 212° F.	Equivalent from 212° F. and at actual steam-pressure.	From actual temperature of feed-water and at actual steam-pressure.	Equivalent from and at 212° F.	Equivalent from 212° F. and at actual steam-pressure.	From actual temperature of feed-water and at actual steam-pressure.	Equivalent from and at 212° F.	Equivalent from 212° F. and at actual steam-pressure.	From actual temperature of feed-water and at actual steam-pressure.	Equivalent from and at 212° F.	Equivalent from 212° F. and at actual steam-pressure.
lbs.	lbs.	lbs.	lbs.	lbs.	lbs.	lbs.	lbs.	lbs.	lbs.	lbs.	lbs.	lbs.	lbs.	lbs.	lbs.	lbs.	lbs.	sq. ft.	sq. ft.	sq. ft.

TABLE II.—*Continued.*

Total Water fed to Boiler.			Average Priming.	Total Water Primed.	Water Evaporated into Dry Steam.			Remarks.
From actual temperature of feed-water and at actual steam-pressure.	Equivalent from and at 212° F.	Equivalent from 212° F. and at actual steam-pressure.			From actual temperature of feed-water and at actual steam-pressure.	Equivalent from and at 212° F.	Equivalent from 212° F. and at actual steam-pressure.	
lbs.	lbs.	lbs.	per cent.	lbs.	lbs.	lbs.	lbs.	

Average Amount of Superheating.	Evaporation from and at 212° F., Equivalent to Total Heat-units derived from Fuel.			Efficiency.			Values of A and B in $F = A\sqrt{H} + B$.		Horse-power.		Remarks.
	Per Pound of Fuel.	Per Pound of Combustible.	Per sq. ft. of Heating-surface per hour.	Experimental.	Estimated.	$R = \frac{\text{Experimental.}}{\text{Estimated.}}$	A	B	Rated.	Actual.	
Fahr.	lbs.	lbs.	lbs.	per cent.	per cent.						

The measurements of the coal were effected by weighing the coal previous to its being wheeled into a pile in the coal-room. The second weighing was made when the coal was fed into the furnace. As far as it was possible, the furnace was supplied with coal at intervals of every half hour, so as to correspond as nearly as could be to the feeding of the water.

After the completion of the test, a careful analysis of the coal was made, to determine upon a sufficiently large scale its calorific power and the quantity of contained moisture. The steam from the boiler was condensed by means of a continuously acting calorimeter, formed by placing four tanks on Fairbanks Standard Platform Scales. The steam from the boiler was passed through a surface-condenser having a condensing surface of 631 sq. ft. As fast as the steam was condensed from the boiler it was received in small tanks located on platform-scales. These tanks were similar in size to the feed-water tanks, and were so arranged as to be filled and emptied once every half hour, one tank receiving the condensed water from the boiler while the other was being emptied.

The condenser was supplied with a large volume of cold water from a weir just outside of the works, and after flowing through the condenser and thereby cooling the steam and receiving therefrom the contained heat, this water was caught in two large tanks placed on platform-scales. These tanks were also arranged so that one tank could be emptied while the other was being filled, and were of sufficient capacity so as to insure catching all of the water required for half an hour's run in the condenser. The temperature of the inlet water of the condenser, of the outlet water, and of the condensed steam were carefully noted by means of thermometers reading to a tenth of a degree. Readings of the inlet water and of the condensed steam were taken once every half hour at the same time that the quantities of the water in the tanks were weighed. Inasmuch as the outlet to the condenser varied considerably in temperature, readings on this were taken every five minutes during the entire time of the test. It will thus be seen that a very correct average of the amount of heat given to the condenser was obtained. The quantity of air supplied

by the blowers to the furnace was measured by continuously acting anemometers placed in the supply-pipes. The readings of the anemometers were checked by means of the number of revolutions of the blowers and their cubic feet per revolution.

The steam-pressure was kept by a recording pressure-gauge, which was checked by an exceedingly delicate and sensitive gauge, which previously, and subsequently to the test, was carefully verified by means of a mercury column. Constant records of the hygrometer, barometer, and thermometers, both in the boiler-room and of the external air, were kept during the entire period of the test.

It will be seen from the above, that all of the processes and measurements were kept in duplicate in such a way as to afford a constant check on each other and preclude the possibility of any errors.

Samples of steam were taken in a small calorimeter for the purpose of ascertaining whether the boiler supplied wet steam.

The following is a brief condensed summary:

EFFICIENCY AS PER TEST, 7.50 A.M. to 7.50 A.M.

Total heat of boiler	64,536,613	heat-units.	
Steam	42,933,141	" "	66.6 per cent.
Heat escaping in flue-gases	9,669,036	" "	15 " "
Radiated heat	5,162,939	" "	8 " "
Heat to vaporize moisture in coal	141,372	" "	0.2 " "
Heat to vaporize moisture in air supplied to furnace	345,978	" "	0.4 " "
Leakage	3,531,645	" "	4.0 " "
" from pump	127,936	" "	0.2 " "
Heat absorbed by fire-brick	2,581,645	" "	4.0 " "
Unaccounted for	1,092,941	" "	1.6 " "

In the trial of an upright boiler reported on by Sir Frederick Bramwell, in 1876, coke being used as the fuel and wood in starting the fires, the following data* were obtained:

Ash and moisture	43.79 lbs.
Combustible	194.46 "
Total fuel	238.25 "
Air used per pound combustible	17½ "

* Conversion of Heat into Work. Anderson.

Heat generated, net	2,798,312	B. T. U.
" " per lb. fuel	11,745	" "
" " available, net	2,101,700	" "
Water evaporated	1,620	lbs.
The efficiency of the furnace was	0.643	"

The balance-sheet stands thus:

Dr.

Available heat	2,101,700	B. T. U.

Cr.

Per Cent.			
88.29	Heat expended in evaporation	1,855,900	B. T. U.
7.03	Displacing atmosphere	147,720	" "
3.35	Loss by conduction and radiation	70,430	" "
.05	Heat in ashes	1,129	" "
1.26	Unaccounted for	25,521	" "
100.00		2,101,700	

The following are data from a trial of a Galloway boiler, as reported to the Edgemoor Iron Co., in the year 1885, by Messrs. G. N. Comly and R. Dawes, and the efficiency too near the theoretical maximum to be often duplicated. The boiler tested was fitted with an "economizer," or feed-water heater, and the power developed was considerably under its rating. The fuel was a Pennsylvania bituminous. The draught was obtained by a high chimney, and was, as shown in the table, quite powerful. The tabular statement is mainly given as illustrating a very compact form of record of results.

TABLE OF RESULTS OF THE TEST OF A GALLOWAY BOILER AT FRANKFORD JUNCTION, PHILADELPHIA, PA.

	Date of Trial	April 8th, 1885.
	Duration of Trial	11¼ hours.
	Height of Stack	200 feet.
	Boiler, seven feet in diameter, twenty-eight feet long.	
DIMENSIONS AND PROPORTIONS:	Grate-surface	35.75 sq. ft.
	Water-heating-surface	853 "
	Superheating-surface	225 "
	Ratio of Water-heating Surface to Grate-surface	23.86 to 1 sq. ft.
	Economizer Heating-surface, per each boiler	609 sq. ft.
AVERAGE PRESSURES:	Force of Draught, in inches, at stack base, after leaving economizer	.75 ins. of water.
	Force of Draught, in inches, at back of boiler, before entering economizer	.5625 "
	Force of Draught, in inches, at front of boiler, before entering economizer	.6063 "
	Absolute Steam-pressure	93.575 pounds.
	Atmospheric Pressure, per barometer	29.975 inches.
	Steam-pressure in boiler, by gauge	78.875 pounds.

Average Temperatures:	Of External Air	58 degrees.
	Of Fire-room	66 "
	Of Steam	381 "
	Of Chimney-flue, escaping gases	200 "
	Of Side-flue, at back end of boiler, escaping gases	360 "
	Of Side-flue, at front end of boiler, escaping gases	589 "
	Of Feed-water	84 "
	Of Feed-water, after leaving economizer, and entering boiler	155 "
Fuel:	Total amount of Coal consumed	6925 pounds.
	Total Refuse from coal	569 "
	Moisture in Coal	301 "
	Total Combustible	6055 "
	Dry Coal consumed, per hour	589 "
	Combustible consumed, per hour	538 "
	Dry Coal consumed, per indicated horse-power, per hour	1.87 "
	Combustible consumed, per indicated horse-power, per hour	1.72 "
Results of Calorimetric Tests:	Quality of Steam, dry steam being taken as unity	1.019984.
	Percentage of Moisture in steam	None.
	Number of Degrees superheated	58 degrees.
Water:	Height of Water in gauge-glasses	4.63 inches.
	Total weight of Water pumped into boiler	68,138 pounds.
	Of this there was used as hot water	2,782 "
	Converted into Steam	65,356 "
	Water actually evaporated, corrected for quality of steam.	66,854 "
	Equivalent Water evaporated into dry steam from and at 212° F.	78,112 "
	Percentage of increase of Evaporative Capacity by using economizer	$6\frac{1}{16}$ per cent.
	Equivalent Water evaporated into dry steam from and at 212° F. per hour	6943 pounds. 116 cubic feet.
	Equivalent total Heat derived from fuel, in British thermal units	75.432885.
	Equivalent total Heat derived from one pound of dry coal	.11389.
	Equivalent total Heat derived from one pound of combustible	.12459.
Economic Evaporation:	Water actually evaporated, per pound of dry coal, from actual pressure and temperature	10.093 pounds.
	Water actually evaporated, per pound of combustible	11.041 "
	Equivalent Water evaporated, per pound of dry coal, from and at 212° F. (Boiler and Economiser used together.)	11.793 "
	Equivalent Water evaporated, per pound of combustible, from and at 212° F. (Boiler and Economiser used together.)	12.907 "
	Equivalent Water evaporated, per pound of combustible, from and at 212° F. (By boiler, exclusive of economiser.)	12.153 "
Rate of Combustion:	Dry Coal actually burned, per square foot of grate-surface, per hour	16.46 "
	Consumption of dry Coal per hour, coal assumed with one sixth refuse, Per square foot of grate-surface	18.07 "
	Consumption of dry Coal per hour, coal assumed with one sixth refuse, Per square foot of water-heating surface	0.745 "

RATE OF EVAPORATION:	Water evaporated from and at 212° F., per square foot of water-heating surface, per hour		8.139 pounds.
	Water evaporated, per hour, from temperature of 100° F. into steam of seventy pounds' gauge-pressure,	Per square foot of grate-surface	168.9 "
		Per square foot of water-heating surface .	7.079 "
	Horse-power of engine, as per indicator-cards taken on day of boiler-test . . .		311.45 horse-power.
	Kind of Coal used		Ocean bituminous.
	Condition of Chimney-damper		58 p.c. of full open'g.
	Cleaned fires, number of times on each furnace during the test		1.

In trials conducted by the Author, for a committee of the American Institute, of which he was chairman, in testing a number of different types of boiler,* a surface-condenser was employed to condense *all* steam made, and results thus for the first time obtained which gave exact measures of net efficiency, the quality of all steam made being determined.

In calculating the results from the record of the logs, the committee first determined the amount of heat carried away by the condensing water by deducting the temperature at which it entered from that at which it passed off. To this quantity is added the heat which was carried away by evaporation from the surface of the tank, as determined by placing a cup of water in the tank at the top of the condenser at such height that the level of the water inside and outside the cup were the same, noting the difference of temperatures of the water in the cup and at the overflow, and the loss by evaporation from the cup. The amount of evaporation from the surface of the water in the cup and in the condenser, which latter was exposed to the air, was considered as approximately proportional to the tension of vapor due their temperatures, and was so taken in the estimate. The excess of heat in the water of condensation over that in the feed-water also evidently came from the fuel, and this quantity was also added to those already mentioned.

* See Transactions, 1871; also, Report on Mechanical Engineering at Vienna International Exhibition, 1873, R. H. T.

The total quantities were, in thermal units, as follows:

A	34,072,058.09
B	48,241,833.60
C	24,004,601.14
D	38,737,217.57
E	11,951,002.10

These quantities, being divided by the weight of combustible used in each boiler during the test, will give a measure of their relative economical efficiency; and, divided by the number of square feet of heating-surface, will indicate their relative capacity for making steam. But as it was the intention of the committee to endeavor to establish a practically correct measure that should serve as a standard of comparison in subsequent trials, it was advisable to correct these amounts by ascertaining how and where errors have entered, and introducing the proper correction. There were two sources of error that are considered to have affected the result as above obtained. The tank being of wood, a considerable quantity of water entered it, leaked out again at the bottom, without increase of temperature, instead of passing through the tank and carrying away the heat, as it is assumed to have done in the above calculation. The meters also registered rather more water than actually passed through them, and this excess assists in making the above figures too high. The sum of these errors the committee estimated at 4 per cent of the total quantity of heat carried away by the condensing water. The other two quantities were considered very nearly correct.

Making these deductions, we have the following as the total heat, in British thermal units, which was thrown into the condenser by each boiler:

A	32,751,835.34
B	46,387,827.10
C	23,066,685.39
D	37,228,739.07
E	11,485,777.35

That the figures thus obtained are very accurate, is shown by calculating the heat transferred to the condenser by the the boilers marked A and B (both of which superheated their

steam), by basing the calculation on the temperature of the steam in the boiler, as given by the thermometer, the results thus obtained being 32,723,681.76 and 46,483,322.5, respectively.

Dividing these totals by the pounds of combustible consumed by each boiler, we get as the quantity of heat per pound, and as a measure of the relative economic efficiency:

A	10,281.53
B	10,246.92
C	10,143.66
D	10,048.24
E	10,964.94

Determining the weight, in pounds, of water evaporated per square foot of heating-surface per hour, we get as a measure of the steaming capacity:

A	2.65
B	3.59
C	2.83
D	3.10
E	1.92

The quantity of heat per pound of combustible, as above determined, being divided by the latent heat of steam at 212° Fahrenheit (966°.6), gives as the equivalent evaporation of water at the pressure of the atmosphere, and with the feed at a temperature of 212° Fahrenheit:

A	10.64
B	10.60
C	10.49
D	10.40
E	10.34

For general purposes this is the most useful method of comparison for economy.

The above figures afford a means of comparison of the boilers, irrespective of the condition (wet or dry) of the steam furnished by them. All other things being equal, however, the committee consider that boiler to excel which furnishes the driest steam; provided that the superheating, if any, does not exceed about 100°.

In this trial the superheating was as follows:

A	16°.08
B	13°.23
C	0.
D	0.
E	0.

As the boilers C, D, E did not superheat, it became an interesting and important problem to determine the quantity of water carried over by each with the steam. This we are able, by the method adopted, to determine with great facility and accuracy.

Each pound of saturated steam transferred to the condensing water the quantity of heat which had been required to raise it from the temperature of the water of condensation to that due to the pressure at which it left the boiler, *plus* the heat required to evaporate it at that temperature. Each pound of water gives up only the quantity of heat required to raise it from the temperature of the water of condensation to that of the steam with which it is mingled. The total amount of heat is made up of two quantities, therefore, and a very simple algebraic equation may be constructed which shall express the conditions of the problem:

Let

$H =$ heat-units transferred per pound of steam.
$h =$ heat-units transferred per pound of water.
$U =$ total quantity of heat transferred to condenser.
$W =$ total weight of steam and water, or of feed-water.
$x =$ total weight of steam.
$W - x =$ total weight of water primed.

Then

$$Hx + h(W - x) = U; \text{ or } x = \frac{\frac{U}{h} - W}{\frac{H}{h} - 1}.$$

Substituting the proper values in this equation, we deter-

mine the absolute weights and percentages of steam and water delivered by the several boilers as follows:

	Weight of Steam.	Weight of Water.	Percentage of Water Primed to Water Evaporated.
A.	27,896.	0.	0.
B.	39,670.	0.	0.
C.	19.782.94	645.06	3.26
D.	31,663.35	2,336.65	6.9
E.	9,855.6	296.9	3.

And the amount of water, in pounds, actually evaporated per pound of combustible:

A.	8.76
B.	8.76
C.	8.70
D.	8.55
E.	9.41

Comparing the above results, the committee were enabled to state the following order of capacity and of economy in the boilers exhibited, and their relative percentage of useful effect, as compared with the economical value of a steam-boiler that should utilize all of the heat contained in the fuel:

	Steaming Capacity.	Economy of Fuel.	Percentage of Economical Effect.
A.	No. 4	No. 2	0.709
B.	No. 1	No. 3	0.707
C.	No. 3	No. 4	0.699
D.	No. 2	No. 5	0.693
E.	No. 5	No. 1	0.756

The results obtained as above, and other very useful determinations derived from this extremely interesting trial, were given in the table, as a valuable standard set of data with which to compare the results of future trials, and as a useful aid in judging of the accuracy of statements made by boiler-venders in the endeavor to effect sales by presenting extravagant claims of economy in fuel.

Mr. Drewitt Halpin found the following net results of test of a variety of English-built boilers:

No.	Description of Boiler.	Pounds Water Evaporated. Per square foot of heating-surface per hour.	Pounds Water Evaporated. Per pound of fuel from and at 212 degrees.	Thermal Units. In fuel.	Thermal Units. Transmitted per hour per sq. ft. heating-surface per hour.	Thermal Units. Per pound fuel.	Efficiency.	*G* figure of merit = units, per sq. ft. per hour × efficiency.
1	Field	4.57	8.83	......	4,414	8,529	..	......
2	Field	2.28	10.83	......	2,202	10,461	..	......
3	Field	2.57	10 93	. ....	2,482	10,558	..	......
4	Portable (Cardiff)	1.52	10.23	14,718	1,468	9,882	67	98,356
5	Portable (Cardiff)	2.26	10.49	14,718	2,183	10,133	68	148.444
6	Portable (Cardiff)	1.76	11.81	14,718	1,700	11.408	77	130.900
7	Portable (Cardiff)	3.56	9.93	.....	3.438	9.592	..	118,248
8	Lancashire	1.57	12.83	15.715	1.516	12,393	77	108.248
9	Lancashire	2.83	9.89	13,833	2,733	9.553	68	185,844
10	Lancashire	1.88	12.25	15,715	1,816	11,833	75	136.200
11	Jacketed	4.70	7.7	14.805	4,595	7.500	50	229.750
12	Lancashire	2.57	10.9	15.715	2,482	10,529	67	166,294
13	Compound	1.43	11.51	14,296	1,381	11,125	78	107,718
14	Loco. (Webb)	9.83	10.28	14.004	9,495	9,930	70	664,650
15	Loco. (Marie)	4.62	10.65	14.600	4,462	10,287	70	312,340
16	Loco. (Coke)	12.57	8.22	13.550	12,142	7.940	58	704,236
17	Loco. (Coke)	13.73	8.94	13,550	13,263	8,636	63	835.569
18	Loco. (Coke)	6.76	10.01	13,550	6.530	9,669	71	463,630
19	Loco. (Coke)	7.39	11.2	13,550	7,138	10,819	77	549.626
20	Torpedo	12.54	8.37	14,727	12,113	8,085	54	654,102
21	Torpedo	14.86	7.78	14,727	14.354	7.523	51	732,054
22	Torpedo	17.90	7.49	14.727	17,291	7,235	49	847.259
23	Torpedo	20.74	7.04	14,727	20,034	6,800	46	921,564
24		*a*	*b*	*c*	*d*	*e*	*f*	*g*

The "locomotive" boiler is found to be more efficient as a part of the engine and on the track than when mounted as a stationary boiler, an unexpected result.

259. **The Quality of Steam** made in any boiler, or as supplied to an engine, is hardly less important than the quantity. When the steam is required for heating purposes simply, or even when all the heat issuing as waste, necessary or other, from the exhaust-ports of a non-condensing engine cylinder can be utilized for useful and paying purposes, this is a matter of no importance; but when it is essential that loss in the engine shall be made a minimum, and that the engine shall have maximum efficiency, the quality of the steam becomes exceedingly important. Dry steam is very much more efficient as a working substance in the steam-engine than wet; since, where the latter is supplied from the boiler, the waste by cylinder-condensation is greatly increased—and so greatly that the more obvious direct loss by the passing of heat through the engine in unavailable form, hot water acting as its vehicle, becomes comparatively small. The determination of the quality

of steam by any boiler is thus as important as the measure of its apparent evaporation.

The difference between the apparent and the actual evaporation is often very great. A good boiler properly managed will usually "prime" less than five per cent, even though having no superheating-surface, and less than two per cent may usually be hoped for. Steam is often made practically dry. But a hard-worked boiler, or one having defective circulation, will often prime ten or twenty per cent; and cases have been found in the experience of the Author in which the quantity of water carried out of the boiler by the current of steam exceeded the weight of the steam itself. It has thus happened that, where no measure of this defect has been made, the apparent evaporation only being reported, the quantity of water said to have been evaporated has equalled, and sometimes has even greatly exceeded, the theoretically possible evaporation of an absolutely perfect boiler. It is thus essential that, when the apparent evaporation has been determined by trial, the quantity of water entrained with the steam be measured and deducted, and then *real* evaporation thus ascertained and reduced for the standard conditions. Under ordinarily good conditions, a real evaporation of ten or eleven times the weight of the fuel, corresponding to an efficiency of 0.75 to 0.80, represents the best practice, and a real evaporation of twelve of water by one of combustible, from and at the boiling-point, or an efficiency of eighty per cent, is rarely observed under the usually best conditions of steam-boiler practice. Where more than the efficiency here given as probable is reported, the work should be very carefully revised, and errors sought until absolute certainty is secured.

Trials not including calorimetric measurement of the water entrained with the steam are comparatively valueless, and should be rejected in any important case. Reports of extraordinary economy are often based on this kind of error. The experiments of M. Hirn at Mulhouse showed an average of about 5 per cent priming; Zeuner makes it approximately from 7½ to 15 per cent; while the experiments of the Author at the American Institute in 1871 give from 3 to 6.9 per cent.

A recently devised method of measuring the amount of moisture in the steam is to introduce into the boiler with the feed-water sulphate of soda, and at intervals to draw from the lower gauge-cock a small amount of water, and also from the steam, condensing either by a coil of pipe in water or a small pipe in air. A chemical analysis gives the proportion of sulphate of soda in each portion, and the quotient of the proportion of sulphate of soda in the portion from the steam by the proportion in that from the water gives the ratio of water entrained, as steam does not carry sulphate of soda, which is only brought over by the hot water entrained. This method was used by Professor Stahlschmidt at the Düsseldorf Exhibition Trials.

260. The Calorimeters used in determining the quantity of moisture in steam have several forms, widely differing in construction, and to some extent in value. They nearly all embody the same principles, however. The objects sought to be attained in their construction are: The exact measurement of the weight of steam received by them from the boiler, and of its temperature and pressure at the boiler; the determination of the weight of water used in its condensation and the range of temperature through which it is raised in the operation: the reduction of wastes of heat in the calorimeter to a minimum, and the exact measurement of that waste if it is sensibly or practically noticeable.

The Barrel or Tank Calorimeter as employed by the Author, is the simplest form of this instrument which has been employed. It consists of a strong barrel or tank, of hard wood, absorbing little of either water or heat, and having a movable cover. This tank is mounted on platform-scales capable of accurate adjustment and having as fine readings as possible. It is filled with water to within about one fourth its height from the top, and the steam is led into it through a rubber tube or hose of sufficient capacity to supply the steam to the amount of one eighth or one tenth the weight of the water in three or five minutes. A steam-gauge of known accuracy gives the boiler-pressure, and the corresponding temperature and total heat of the steam are ascertained from the steam-tables.

In using this apparatus the steam is rapidly passed into the mass of water contained in the tank, until the scales show that the desired quantity has been added. The steam is so directed by varying the position of the end of the tube, and by inserting it so deeply in the water that the whole mass is very thoroughly stirred, and a very perfect mixture secured of condensing water with the water of condensation; and so that the temperatures indicated by the inserted thermometer shall be the real mean temperature of the mass. The weights and

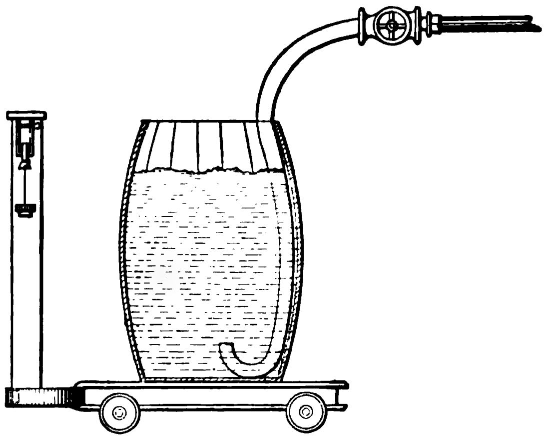

FIG. 118.—THE CALORIMETER.

temperatures are then inserted in the log of the trial, as below, and the proportion of water brought over with the steam is thence easily calculable. The thermometers employed usually read to tenths of a degree Fahrenheit, or to twentieths of a centigrade degree, accordingly as the one or the other scale is employed. Readings must be made with the greatest possible accuracy, and in sufficient number to insure a satisfactorily exact mean. With good thermometers and scales, a reliable gauge, and care in operation, good results can be obtained by averaging a series of trials.*

The **Hirn Calorimeter** is substantially the same as the above, with the addition of an apparatus for stirring the water

* Report on Boiler Trial, Trans. A. S. M. E. 1884, vol. vi.

in the tank to insure thorough mixture and readings of temperature of condensing water exactly representative of the true mean temperature of the mass after the introduction of the steam. This is not an essential feature of the apparatus, if the Author may judge by his own experience, provided the jet of entering steam is so directed as to cause rapid circulation. No stirring apparatus could operate more efficiently than the force of the steam itself, properly directed. Hirn was probably the first (1868) to attempt the determination of the quality of steam as delivered from steam-boilers.* A similar apparatus was used at the trials of the Centennial International Exhibition, Philadelphia, 1876.†

261. The Theory of the Calorimeter is as follows:‡

Each pound of saturated steam transferred to the condensing water the quantity of heat which had been required to raise it from the temperature of the water of condensation to that due to the pressure at which it left the boiler, *plus* the heat required to evaporate it at that temperature. Each pound of water gives up only the quantity of heat required to raise it from the temperature of the water of condensation to that of the steam, with which it is mingled. The total amount of heat is made up of two quantities, therefore, and a very simple algebraic equation may be constructed, which shall express the conditions of the problem:

Let, as in § 258,

$H =$ heat-units transferred per pound of steam;
$h =$ heat-units transferred per pound of water;
$U =$ total quantity of heat transferred to condenser;
$w =$ total weight of steam and water, or of feed-water;
$x =$ total weight of steam; $W =$ condensing water;
$w - x =$ total weight of water primed.

* Bulletin de la Société Industrielle de Mulhouse, 1868–9.

† Reports of Judges, vol. vi.

‡ First published by the Author, who had not then become aware of the work done by M. Hirn, in Trans. Am. Inst. Report on Boiler Trial, 1871. See also Vienna Reports, vol. iii. p. 123.

Then

$$Hx + h(w - x) = U; \quad \text{or} \quad x = \frac{\frac{U}{h} - w}{\frac{H}{h} - 1} = \frac{U - wh}{H - h}.$$

Substituting the proper values in this equation, we determine the absolute weights and percentages of steam and water delivered by the boiler.

Or, let

Q = quality of the steam, dry saturated steam being unity;
H' = total heat of steam at observed pressure;
T = " " " water " " .
h' = " " " condensing water, original;
h_1 = " " " " " final.

And we have the equivalent expression, as written by Mr. Kent,

$$Q = \frac{1}{H' - T}\left[\left(\frac{W}{w}(h' - h_1)\right) - \left(T - h_1\right)\right].$$

The value of the quantity U is obtained by multiplying the weight of water in the calorimeter originally by the range of temperature caused by the introduction of the steam from the boiler. Mr. Emery employs another form, as below, in which Q is the quality of steam as before; W the weight of condensing water; w the weight added from the boiler; T the temperature due the steam-pressure in the boiler; t the initial and t_1 the final temperature of the calorimeter; l the latent heat of evaporation of the boiler-steam; and x the weight of steam corresponding to l. Thus,

$$x = \frac{W(t_1 - t) - w(T - t_1)}{l}, \quad y = 100\frac{w - x}{w};$$

and

$$Q = \frac{x}{w} = \frac{W(t_1 - t) - w(T - t_1)}{lw}.$$

If Q exceeds unity, the steam is superheated by the amount

$$\frac{(Q-1)l}{0.48} = 2.0833l\,(Q-l);*$$

and if less than unity, the priming is, in per cent, $100\,(1-Q)$.

262. Records of calorimetric tests should be even more carefully and more frequently made than in any other part of the work of a boiler-trial. The following, from work conducted by the Author, illustrates the method. The symbols relate to the first of the above formulas.

PRIMING TESTS.

Steam-pressure.	W Weight Condensing Water.	w Weight Wet Steam added.	T Temperature of Cold Water.	T' Resultant Temperature.	Total heat in Dry Steam.	$H-T'$	$\frac{W}{w}$	$T'-T$	l	– % Moisture.
100	290	10	50.8	83.4	1185.0	1001.6	29	32.6	875.4	.06
100	290	27.5	50.8	138.8	1185.0	1046.2	10.5	88	875.4	.13
100	327.5	10	55.8	85.8	1185.0	1099.2	32.75	30	875.4	.13
100	327.5	15	55.8	100.2	1185.0	1084.8	21.83	44.4	875.4	.13
100	332.0	10	99.2	125.6	1185.0	959.4	33.2	26.4	875.4	.09
100	332.0	15½	99.2	139.2	1185.0	945.8	21.1	40.0	875.4	.10
100	315.0	15	56.2	102.8	1185.0	1082.2	21.0	46.6	875.4	.11
100	315.0	25	56.2	130.0	1185.0	1055.0	12.6	73.8	875.4	.13

The boiler was a water-tubular boiler, which was not so handled as to give as dry steam as was desired; and one object of the trial, of which the above is a part of the record, was to ascertain how seriously was the quality of the steam affected. It is seen that the priming amounted to ten or twelve per cent, with fairly uniform figures through the period of test. The steam should have entrained less than even this proportion, had the boiler been all that was expected of it.

Errors of small magnitude, absolutely, may greatly affect the results of calculation, as is well illustrated by the following example presented by Mr. Kent:

* Centennial Report, pp. 138-9.

Assume the values of the quantities to be, as read, column 1:

	Observed Reading.	True Reading.	Amount of Error.
Weight of condensing water, corrected for equivalent of apparatus,* W	200.5 lbs.	200 lbs.	½ pound.
Weight of condensed steam, w	9.9 "	10.0 "	$\frac{1}{10}$ "
Pressure of steam by gauge, P	78. "	80 "	2 pounds.
Original temperature of condensing water, t	44°.5 "	45° "	½ degree.
Final temperature of condensing water, t'	100°.5 "	100° "	½ "

Then let it be assumed that errors of instruments or of observation have led to the recording of slightly different figures from the true quantities, as given in column 2:

		Moisture per cent.	Error per cent.
Substituting in the formula the "true readings," we have for the value of	$Q = 0.9874$	$= 1.26$	$= 0.$
All readings true except $W = 200.5$,	$Q = .9906$	$= 0.94$	$= 0.32$
" " " " $w = 9.9$,	$Q = 1.0000$	$= 0.00$	$= 1.26$
" " " " $P = 78.0$,	$Q = .9880$	$= 1.20$	$= 0.06$
" " " " $t = 44.5$,	$Q = .9989$	$= 0.11$	$= 1.15$
" " " " $t' = 100.5$,	$Q = .9994$	$= 0.06$	$= 1.20$
" " incorrect	$Q = 1.0272$	$=$ (minus)	$= 3.98$

The last case is equivalent to 50.2 degrees superheating.

Errors of 0.1 or even 0.25 per cent in weights and of temperature of equal amount not infrequently occur, probably, where ordinary instruments are employed. The errors due to false weight in measurement of the condensed steam are liable to be very serious, and it is only by making a considerable number of observations and obtaining the mean that results can be secured, ordinarily, of real value.

263. The "Coil Calorimeter" has been devised to secure more exact results in the weighing of the water of condensation than can be obtained when it is weighed as part of the larger mass. In this instrument a coil of pipe is introduced into the tank and serves as a surface-condenser in which the boiler-steam is received and condensed, and from which it is transferred to another vessel in which it is weighed by itself with scales constructed to weigh such small weights with accuracy; or the coil is removed and weighed with the contained water. In the

* Correction made only for coil calorimeter to be described.

former case, drops of water may adhere to the internal surfaces of the coil and escape measurement; in the latter, the weight to be determined is increased by the known weight of the coil, and less delicacy of weighing becomes possible.

The following is Kent's description of his calorimeter, which is of this class, and has been found to give good results: *

A surface-condenser is made of light-weight copper tubing $\frac{3}{4}''$ in diameter and about 50′ in length, coiled into two coils, one inside of the other, the outer coil 14″ and the inner 10″ in diameter, both coils being 15″ high. The lower ends of the coils are connected by means of a brazed T-coupling to a shorter coil, about 5′ long, of 2″ copper tubing, which is placed at the bottom of the smaller coil and acts as a receiver to contain the condensed water. The larger coil is brazed to a $\frac{3}{4}''$ pipe, which passes upward alongside of the outer coil to just above the level of the top of the coil and ends in a globe-valve, and a short elbow-pipe which points outward from the coil. The upper ends of the two $\frac{3}{4}''$ coils are brazed together into a T, and connected thereby to a $\frac{3}{4}''$ vertical pipe provided with a globe-valve, immediately above which is placed a three-way cock, and above that a brass union ground steam-tight. The upper portion of the union is connected to the steam-hose, which latter is thoroughly felted down to the union. The three-way cock has a piece of pipe a few inches long attached to its middle outlet and pointing outward from the coil.

A water-barrel, large enough to receive the coil and with some space to spare, is lined with a cylindrical vessel of galvanized iron. The space between the iron and the wood of the barrel is filled with hair-felt. The iron lining is made to return over the edge of the barrel, and is nailed down to the outer edge so as to keep the felt always dry. The barrel is furnished also with a small propeller, the shaft of which runs inside of the inner coil when the latter is placed in the barrel. The barrel is hung on trunnions by a bail by which it may be raised for weighing on a steelyard supported on a tripod and lifting lever. The steelyard for weighing the barrel is graduated

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* Trans. Am. Soc. M. E. 1884.

to tenths of a pound, and a smaller steelyard is used for weighing the coil, which is graduated to hundredths of a pound.

In operation, the coil, thoroughly dry inside and out, is carefully weighed on the small steelyard. It is then placed in the barrel, which is filled with cold water up to the level of the top of the globe-valves of the coil and just below the level of the three-way cock, the propeller being inserted and its handle connected. The barrel and its contents are carefully weighed on the large steelyard; the steam-hose is connected by means of its union to the coil, and the three-way cock turned so as to let the steam flow through it into the outer air, by which means the hose is thoroughly heated; but no steam is allowed to go into the coil. The water in the barrel is now rapidly stirred in reverse directions by the propeller and its temperature taken. The three-way cock is then quickly turned, so as to stop the steam escaping into the air and to turn it into the coil; the thermometer is held in the barrel, and the water stirred until the thermometer indicates from five to ten degrees less than the maximum temperature desired. The globe-valve leading to the coil is then rapidly and tightly closed, the three-way cock turned to let the steam in the hose escape into the air, and the steam entering the hose shut off. During this time the water is being stirred, and the observer carefully notes the thermometer until the maximum temperature is reached, which is recorded as the final temperature of the condensing water. The union is then disconnected and the barrel and coil weighed together on the large steelyard; the coil is then withdrawn from the barrel and hung up to dry thoroughly on the outside. When dry it is weighed on the small scales. If the temperature of the water in the barrel is raised to 110° or 120° the coil will dry to constant weight in a few minutes. After the weight is taken, both globe-valves to the coil are opened, the steam-hose connected, and all of the condensed water blown out of the coil, and steam allowed to blow through the coil freely for a few seconds at full pressure. When the coil cools it may be weighed again, and is then ready for another test.

If both steelyards were perfectly accurate, and there were no losses by leakage or evaporation, the difference between the

original and final weights of the barrel and contents should be exactly the same as the difference between the original and final weights of the coil. In practice this is rarely found to be the case, since there is a slight possible error in each weighing, which is larger in the weighing on the large steelyard. In making calculations the weights of the coil on the small steelyard should be used, the weight on the large steelyard being used merely as a check against large errors.

The late Mr. J. C. Hoadley constructed exceedingly accurate apparatus of the "coil" type and obtained excellent results.

It is evident that this calorimeter may be used continuously, if desired, instead of intermittently. In this case a continuous flow of condensing water into and out of the barrel must be established, and the temperature of inflow and outflow and of the condensed steam read at short intervals of time.

264. **The Continuous Calorimeter** is an instrument in which the operations of transfer of steam to the instrument and its examination are not intermitted, as is necessarily the case in the more commonly employed forms of the apparatus. The instrument being thus kept in use continuously, every variation in the quality of steam can be observed and the number of observations can be increased to any desired extent, and, the apparatus being accurate, any degree of exactness of mean results can be attained.

One of the earliest forms of this instrument was devised by Mr. John D. Van Buren, of the U. S. N. Engineers, and Instructor in Engineering at the Naval Academy, about 1867. This instrument, as constructed by Mr. T. Skeel, and used by a committee of judges* at the exhibition of the American Institute, 1874–5, of which the Author was chairman, was made as follows:

Steam was drawn from the steam-drum, near the safety-valve, through a felted pipe $1\frac{1}{2}$ inches (3.8 cm.) diameter, into a rectangular spiral or coil consisting of 80 feet (24.4 m.) of pipe of similar size. Condensing water from the street-main was led into the tank surrounding the coil or "worm," and

* Trans. Am. Inst. 1875; Van Nostrand's Mag. 1875.

issued at the bottom through a "standard orifice," the rate of discharge from which had been determined and the law of its variation with change of head ascertained. The quantity of condensing water thus became known by observing the head of water within the tank. The water of condensation from the coil was caught in a convenient vessel, and weighed on scales provided for that purpose. The temperature of the condensing water at entrance and exit was shown by fixed thermometers, and that of the water of condensation at its issue from the coil was similarly shown, while the steam-gauge placed on the boiler gave the other needed data. The calculations are evidently precisely the same as with the preceding type of calorimeter.

*The Barrus Calorimeter** (Fig. 119) is essentially of a small surface-condenser. The steam enters by the pipe *j*. The condensing-surface, *a*, is a continuation and enlargement of the supply-pipe, a 1-inch (2.54 cm.) iron pipe with a length of 12 inches (30.4 cm.) of exposed surface. This pipe is under the full pressure of steam. The condensed water collects in the lower parts of the apparatus, where its level is shown in the glass, *c*, and is drawn off by means of the valve, *d*. The injection-water, cooled to a temperature of 40° Fahr., or less, enters the wooden vessel, *o*, through the valve, *b*, and circulates around the condensing pipe, carried downward to the bottom by means of the tube *k*, and overflows at the pipe, *c*, after passing through the mixing chambers, *m*. The amount of water admitted is regulated so as to secure a temperature at the overflow of 75° or 80° Fahr., or the approximate temperature of the surrounding atmosphere. The thermometers, *f* and *g*, which are read to

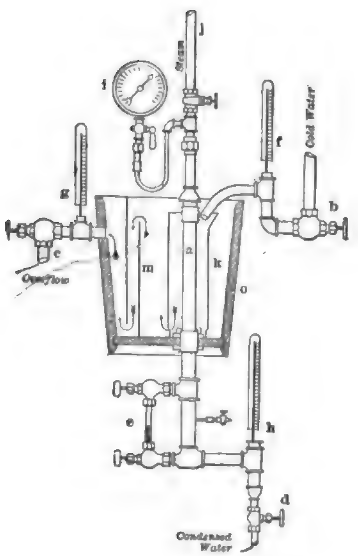

FIG. 119.—THE CONTINUOUS CALORIMETER.

* Trans. Am. Soc. M. E. 1884.

tenths of a degree, show the temperature of injection and overflow water, and the thermometer, *h*, shows that of the condensed water. The overflow water and the condensed water are collected in a system of weighing tanks. The steam-pipe down to the surface of the water, and the pipes in the lower part of the apparatus, are covered with felt.

There is no wire-drawing of the steam, and no allowance to be made for specific heat of the apparatus. The only correction to be made of material amount is for radiation from the pipes covered with felt, and this can be accurately determined by an independent radiation experiment, made when the condenser vessel is empty.

Another form of instrument devised by the same engineer is arranged in such manner as to permit the steam from the boiler to be dried and the quantity of heat so employed measured as a gauge of the amount of water contained in the steam. This form of this apparatus is found very satisfactory.*

The pipe conveying the steam to be tested is usually a half-inch (1.27 cm.) iron pipe. A long thread is cut on this pipe, and it is screwed into the main steam supply-pipe of the boiler in such a manner as to extend diametrically across to the opposite side. The inclosed part is perforated with from 40 to 50 small holes, and the open end of the pipe sealed. If the pipe is screwed into the under side the perforations begin at a distance of one inch (2.54 cm.) from the bottom. The connection is made as short as possible, and covered with felt. Where the calorimeter can be attached to the under side of the main, the distance to the top valve need not exceed six inches (15 cm.). In this position it is self-supporting. The steam for the superheater is also supplied by a half-inch iron pipe, but this may be attached to the main at any convenient point.

Steam to be tested enters by the pipe, which has a jacket. On passing out the thermometer gives its temperature, and it is discharged through a small orifice $\frac{1}{8}$ inch (0.32 cm.) in diameter. Steam to be superheated enters and is superheated by a gas-lamp, passes the thermometer,

* Trans. Am. Soc. Mach. Engrs., vol. vii. p. 178.

and issues through an opening like that for the steam. The thermometers are immersed in oil-wells surrounded by the current of steam to be tested, or of that used in drying the boiler-steam.

In the operation of this calorimeter steam at full pressure enters the apparatus, and the jacket-steam is heated until a perceptible rise of temperature above that due the pressure indicates that its moisture has been evaporated. The working having become steady, the difference between the temperatures is noted and corrected by deducting the excess above that of moist steam at the observed pressure, and the number of degrees of superheating thus determined, as the rate of flow is the same from both orifices. Here the evaporation of one per cent of moisture from steam at 80 pounds pressure (5.6 kilogs. per sq. cm.) reduces the temperature of superheated steam about 18°.7 Fahr. (10°.4 Cent.), and the percentage of moisture is obtained by dividing the range of superheat, as above, by this number, or generally by the quotient of the latent heat at the observed pressure by 47.5. The following are data and results obtained by the use of this apparatus:

DATA AND RESULTS IN FULL OF CALORIMETER TESTS.

Number for Reference.	Date.	Gauge-pressure.	Number of degrees inlet steam was superheated.	Number of degrees outlet steam was superheated.	Number of degrees wet steam was superheated.	Number of degrees lost by superheated steam due to radiation from calorimeter.	Number of degrees representing radiation from supply-pipe.	Amount of Moisture in the Wet Steam.	
								Expressed in degrees of superheat.	Expressed in percentage.*
1	Apr. 13	89.	99.	54.5	8.	8.	9.5	19.	1.02
2	" 14	89.	75.	37.	5.5	8.	9.5	16.	0.86
3	" 15	86.	74.	37.	7.	10.5	9.5	10.	0.54
4	" 16	86.	74.	39.	9.5	7.	9.5	9.	0.49
5	" 30	85.	72.	38.	10.5	8.	9.5	6.	0.32
6	May 4	80.	77.5	41.5	9.5	8.	9.5	9.	0.49
7	" 5	84.	68.	36.5	6.5	7.5	9.5	8.	0.43

NOTE.—The duration of each of these tests was about one hour.

* Obtained by dividing the preceding column by 18.6, the number of degrees corresponding to 1 per cent of moisture.

Many other forms of calorimeter have been devised, but space will not permit their description.

265. The Analysis of Gases* issuing from the furnace and passing up the chimney is sometimes an important detail of the work of testing a steam-boiler. Such an investigation involves only an operation of great simplicity which can easily be performed by any engineer. If it is not found convenient to make the analysis in the office of the engineer, he can have the work done, at little expense, by a chemist of known skill and reliability. It is only by a knowledge of the proportions of constituents of the flue-gases that it can be determined whether the combustion is complete, whether the products of combustion are diluted with excess of air, and whether the fuel used has been so burned as to give its best effect. Such analyses also enable the engineer to ascertain the best method of burning the fuel.

In sampling the gases, a matter in regard to which some precaution is advisable, the method of Mr. Hoadly is found very satisfactory.†

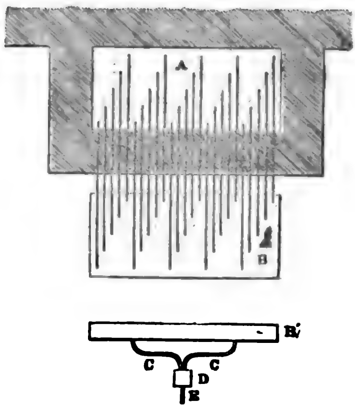

FIG. 119.—FLUE-GAS SAMPLING.

Very great diversities in composition often exist in the same flue at the same time. To obtain a sample, allow one orifice to draw off gases through for each 25 sq. inches (161 sq. cm.) of cross-section of flue. The pipes must be of equal diameter and of equal length. These should be secured in a box of galvanized sheet-iron, equal in thickness to one course of brick, so that the ends may be evenly distributed over the flue *A* (Fig. 119), and their other open ends inclosed in the

* Consult Handbook of Gas Analysis, by C. Winkler. London: J. Van Voorst. 1885.

† Trans. Am. Soc. M. E., vol. vi.

receiver B. If the flue gases be drawn off from the receiver B by four tubes CC, into a mixing box D, beneath, a good mixture can be obtained.

The sampling of the gas should be carried out at intervals of 10 to 15 minutes throughout the trial. The gas should be received in an air-tight pipe or jar. The composition of the gases should be determined as far as regards carbonic acid, carbonic oxide, and oxygen. The tube should be of porcelain or glass for very hot flues, since iron tubes at such temperatures are oxidized. Supposing an analysis of the gas give K per cent of carbonic acid, O per cent of oxygen, and N per cent of nitrogen, then the proportion of air actually used to the theoretical quantity required is 1 to x.

Where

$$x = \frac{N}{N - \frac{79}{21}O} \text{ or } \frac{21}{21 - 79\frac{O}{N}},$$

unity of weight of this coal will then give, at a temperature of 0° and a pressure of one atmosphere,

$$\frac{1854}{10}C = \text{carbonic acid};$$

$$\frac{KO}{K} = \text{oxygen}:$$

$$\frac{KN}{K} = \text{nitrogen}.$$

The quantity of moisture in the escaping gases may be calculated from the moisture in the coal, from that formed by burning the hydrogen, and from that contained in the air admitted to the furnace where the latter has been determined. Any serious break in the setting can be detected by filling the grate with smoky coal and then closing the damper.

The apparatus designed by Professor Elliott, and employed in work carried on under the direction of the Author, consists,

as shown in Fig. 121, of two vertical glass tubes, *AB*, *A'B'*, joined by rubber-tubing, *E*, at their upper ends. The large tube, *AB*, is the treating, the smaller, *A'B'*, the measuring tube; the latter is suitably graduated to cubic centimetres. Water-bottles, *K*, *L*, are connected with the lower ends of the tubes by tubing, *NO*, *N'O'*, and are used in effecting transfer of the gas from tube to tube. *M* is a funnel through which the reagents used may be introduced. *G*, *F*, and *I* are cocks of suitable size and construction.

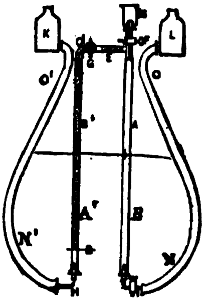

FIG. 121.—APPARATUS FOR GAS ANALYSIS.

In filling the apparatus it is set up conveniently near the flue, and the line of tubing from the collector, within the latter, is connected with the tube *AB*. The receiver *L* being detached the lower end of *AB* is connected with an aspirator or equivalent apparatus, such, for example, as might be improvised by the use of an air-tight tank or a barrel; and the flow thus produced, when the aspirator is emptied of its water, fills the tube *AB* with gas drawn from the flue. It is retained by closing the valves *F* and *I*, which had been open during the operation of filling. The tube is then disconnected from the aspirator, and the receiver, or bottle, *L*, connected as shown, and in such manner that no air can reach the tube *AB*.

Removing the apparatus to the laboratory or other convenient location, the analysis is made as follows:

Pass into *A'B'* a convenient volume, as 100 c.c. of the gas, and discharge the remainder through the valve and funnel *F* and *M*, filling the tube *AB* with water from *L*. Transfer the measured gas back to *AB*, through *E*, and add a solution from *M*, which will absorb some one constituent. Return the gas to *A'B'*, and again read its volumes. The difference is the quantity of gas absorbed. Repeat this process, using next an absorbent which will take up a second constituent of the gas, and thus obtain a second measure of volume; and thus continue until all the desired determinations are made. All readings should be made at the same temperature, or practically so. The tube

AB should be well washed at each operation, in order that no reagent should be affected by traces of that previously used.

The absorbents employed are best taken in the following order:

1. Caustic potash—to absorb carbonic acid.
2. Potassium pyrogallate—to absorb free oxygen.
3. Cuprous chloride in concentrated hydrochloric-acid solution—to absorb carbonic oxide.

After their use nitrogen will remain, and will be measured as a balance which, added to the sum of the measured volumes of gases absorbed, should give the original total. Where weights are to be determined, the volumetric measures obtained as above are to be reduced by the usual process.

The atomic weights of the principal constituents being, oxygen, 16; nitrogen, 14; carbon monoxide, 28; carbon dioxide, 44, we shall have by percentages, where the symbols represent per cent in volumes, for each, when the total is

$$M = 14N + 16O + 28CO + 44CO_2,$$

$$\frac{14N}{M}, \quad \frac{16O}{M}, \quad \frac{28CO}{M}, \quad \frac{44CO_2}{M}, \text{ respectively.}$$

Since the total per cent of oxygen is measured by $\frac{32}{44}CO_2 + \frac{16}{28}CO +$ free oxygen, and the total per cent of carbon is $\frac{12}{44}CO_2 + \frac{12}{28}CO$, we shall have for the percentage of each,

$$O' = \frac{32 \times 44 \times CO_2}{44M} + \frac{16 \times 28 \times CO}{28M} + \frac{16O}{M};$$

$$C' = \frac{12 \times 44 \times CO_2}{44M} + \frac{12 \times 28 \times CO}{28M};$$

or,

$$O' = 32\frac{CO_2}{M} + 16\frac{(CO + O)}{M};$$

$$C' = 12\frac{CO_2}{M} + 12\frac{CO}{M}.$$

The total oxygen is that which entered the furnace as the supporter of combustion, and is a measure of the air supplied. The ratio of free to combined oxygen is a measure of the ratio of the air acting as a diluent simply to that supporting combustion.

Thus these measurements exhibit the efficiency of combustion, the quantity of air employed, and the magnitude of the wastes of heat at the chimney, occurring through imperfect combustion or excess of air-supply. It is evident, however, that where moisture or steam accompanies the gases, it escapes measurement; this, however, introduces no important error in ordinary work.

266. Efficiency of Combustion is indicated by the analysis of the flue-gases with very great certainty. The appearance of carbon monoxide at the chimney proves the combustion to be imperfect in proportion as it is more or less abundant. The presence of unconsumed oxygen, on the other hand, in the absence of carbon monoxide, proves an excess of air-supply. Both gases appearing is a proof of incomplete intermixture of air and combustible, or of so low a temperature of furnace as to check combustion. This analysis being compared with that of the fuel reveals the character and the perfection of combustion, and permits a very exact determination to be made of the specific heat of the gases, and is thus a check on calculations of wasted heat.

267. Draught-gauges are made for the purpose of determining the head-producing draught and the intensity of the draught, which are of many forms, but which usually depend upon the measurement of the head of water which balances that head at the chimney. A very compact and accurate form

of draught-gauge, used by the Author with very satisfactory results, is that of Mr. J. M. Allen (Fig. 122).

A and *A'* are glass tubes, mounted as shown, communicating with each other by a passage through the base, which may be closed by means of the stop-cock shown. Surrounding the glass tubes are two brass rings, *B* and *B'*. These rings are attached to blocks which slide in dovetailed grooves in the

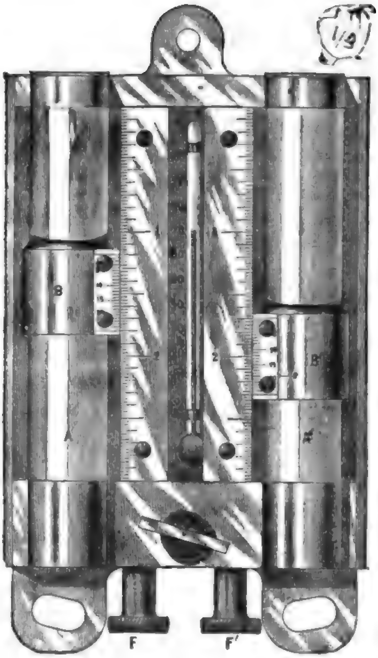

FIG. 122.—DRAUGHT-GAUGE.

body of the instrument, and may be moved up and down by screws at *F F'*. The scales are divided into fortieths of an inch, and read to thousandths of an inch by the verniers *e* and *e'*, which are attached to the sliding rings *B B'*. If the two short rings are set at different heights, the difference in readings will give the difference of level. The thermometer is for the purpose of noting the temperature of the external air. The method of using the instrument is as follows:* At a con-

* *The Locomotive*, May, 1884, p. 67.

venient point near the base of the chimney a hole is made large enough to insert a thermometer. The height from this opening to the top of chimney, and also of grates, should be noted. The chimney-gauge is attached to some convenient wall. The tubes are filled about half full of water, when the verniers afford an easy means of setting it perpendicular. One end of a flexible rubber tube is then inserted into the upper end of one of the glass tubes, and the other end of the tube is in the chimney-flue. The tubes B B' are adjusted until their upper ends are just tangent to the surface of the water in the two tubes. The reading of the two scales is then taken, and their difference. At the same time the temperature of the flue is noted, as well as that of the external atmosphere. Comparison may then be made with the following table, computed for use in this connection for a chimney 100 feet high, with various temperatures outside and inside of the flue, and on the supposition that the ***temperature of the chimney is uniform from top to bottom***—an inaccurate though usual assumption, however. For other heights than 100 feet, the theoretical height is found by simple proportion, thus: Suppose the external temperature is 60°, temperature of flue 380°, height of chimney 137 feet, then under 60° at the top of the table, and opposite to 380° interpolated in the left-hand margin, we find .52″.

Then 100 : 137 :: .52″ : .71″, which is the required height for a 137-foot chimney, and similarly for any other height.

HEIGHT OF WATER COLUMN DUE TO UNBALANCED PRESSURE IN CHIMNEY 100 FEET HIGH.

Temperature in the Chimney. Fahr.	Temperature (Fahr.) of the External Air—Barometer, 14.7.				
	20°	40°	60°	80°	100°
220	.419	.355	.298	.244	.192
250	.468	.405	.347	.294	.242
300	.541	.478	.420	.367	.315
350	.607	.543	.486	.432	.380
400	.662	.598	.541	.488	.436
450	.714	.651	.593	.540	.488
500	.760	.697	.639	.586	.534

CHAPTER XV.

STEAM-BOILER EXPLOSIONS.*

268. Steam-boiler Explosions are among the most terrible and disastrous of all the many kinds of accident, the introduction of which has marked the advancement of civilization and its material progress. Introduced by Captain Savery at the beginning of the 18th century with the first attempts to apply steam-power to useful purposes, they have increased in frequency and in their destructiveness of life and property continually, with increasing steam-pressures and the unintermitted growth of these magazines of stored energy, until to-day the amount of available energy so held in control, and liable at times to break loose, is often as much as two or even three millions of foot-pounds (276,500 to 414,760 kilogrammetres), and sufficient to raise the enclosing vessel 10,000 or even 20,000 feet (3048 to 6096 m.) into the air, the fluid having a total energy, pound for pound, only comparable with that of gunpowder.

In this and the following article it is proposed to present the results of a series of calculations relating to the magnitude of the available energy contained in masses of steam and of water in steam-boilers. This energy has been seen to be measured by the amount of work which may be obtained by the gradual reduction of the temperature of the mass to that due atmospheric pressure by continuous expansion.

The subject is one which has often attracted the attention of both the man of science and the engineer. Its importance, both from the standpoint of pure science and from that of science applied in engineering and the minor arts, is such as

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* This chapter has been separately printed with slight modifications as a monograph "On Steam-boiler Explosions," and published by the Messrs. Wiley.

would justify the expenditure of vastly more time and attention than has yet ever been given it. Mr. Airy * and Professor Rankine † published papers on this subject in the same number of the *Philosophical Magazine* (Nov. 1863), the one dated the 3d September and the other the 5th October of that year. The former had already presented an abstract of his work at the meeting of the British Association of that year.

In the first of these papers it is remarked that "very little of the destructive effect of an explosion is due to the steam which is confined in the steam-chamber at the moment of the explosion. The rupture of the boiler is due to the expansive power common at the moment to the steam and the water, both at a temperature higher than the boiling-point; but as soon as the steam escapes, and thereby diminishes the compressive force upon the water, a new issue of steam takes place from the water, reducing its temperature; when this escapes, and further diminishes the compressive force, another issue of steam of lower elastic force from the water takes place, again reducing its temperature: and so on, till at length the temperature of the water is reduced to the atmospheric boiling-point, and the pressure of the steam (or rather the excess of steam-pressure over atmospheric pressure) is reduced to 0."

Thus it is shown that it is the enormous quantity of steam so produced from the water, during this continuous but exceedingly rapid operation, that produces the destructive effect of steam-boiler explosions. The action of the steam which may happen to be present in the steam-space at the instant of rupture is considered unimportant.

Mr. Airy had, as early as 1849, endeavored to determine the magnitude of the effect thus capable of being produced, but had been unable to do so in consequence of deficiency of data. His determinations, as published finally, were made at his request by Professor W. H. Miller. The data used are the results of the experiments of Regnault and of Fairbairn and Tate on the relations of pressure, volume, and temperature of steam, and of an experi-

* "Numerical Expression of the Destructive Energy in the Explosions of Steam-boilers."

† "On the Expansive Energy of Heated Water."

ment by Mr. George Biddle, by which it was found that a locomotive boiler, at four atmospheres pressure, discharged one eighth of its liquid contents by the process of continuous vaporization above outlined, when, the fire being removed, the pressure was reduced to that of the atmosphere. The process of calculation assumes the steam so formed to be applied to do work expanding down to the boiling-point, in the operation. The work so done is compared with that of exploding gunpowder, and the conclusion finally reached is that "the destructive energy of one cubic foot of water, at a temperature which produces the pressure of 60 lbs. to the square inch, is equal to that of one pound of gunpowder."

The work of Rankine is more exact and more complete, as well as of greater practical utility. The method adopted is that to be described presently, and involves the application of the formulas for the transformation of heat into work which had been ten years earlier derived by Rankine and by Clausius, independently. This paper would seem to have been brought out by the suggestion made by Airy at the meeting of the British Association. Rankine shows that the energy developed during this, which is an adiabatic method of expansion, depends solely upon the specific heat and the temperatures at the beginning and the end of the expansion, and has no dependence, in any manner, upon any other physical properties of the liquid. He then shows how the quantity of energy latent in heated water may be calculated, and gives, in illustration, the amount so determined for eight temperatures exceeding the boiling-point.

This subject attracted the attention of the engineer at a very early date. Familiarity with the destructive effects of steam-boiler explosions, the singular mystery that has been supposed to surround their causes, the frequent calls made upon him, in the course of professional practice and of his studies, to examine the subject and to give advice in matters relating to the use of steam, and many other hardly less controlling circumstances, invest this matter with an extraordinary interest.

A steam-boiler is a vessel in which is confined a mass of water, and of steam, at a high temperature, and at a pressure greatly in excess of that of the surrounding atmosphere. The

sudden expansion of this mass from its initial pressure down to that of the external air, occurring against the resistance of its "shell" or other masses of matter, may develop a very great amount of work by the transformation of its heat into mechanical energy, and may cause, as daily occurring accidents remind us, an enormous destruction of life and property. The enclosed fluid consists, in most cases, of a small weight of steam and a great weight of water. In a boiler of a once common and still not uncommon marine type, the Author found the weight of steam to be less than 250 pounds, while the weight of water was nearly 40,000 pounds. As will be seen later, under such conditions, the quantity of energy stored in the water is vastly in excess of that contained in the steam, notwithstanding the fact that the amount of energy per unit of weight of fluid is enormously the greater in the steam. A pound of steam, at a pressure of six atmospheres (88.2 pounds per square inch), above zero of pressure, and at its normal temperature, 177 C. (319° F.), has stored in it about 75 British thermal units (32 calories), or nearly 70,000 foot-pounds of mechanical energy per unit of weight, in excess of that which it contains after expansion to atmospheric pressure. A pound of water accompanying that steam, and at the same pressure, has stored within it but about one tenth as much available energy. Nevertheless, the disproportion of weight of the two fluids is so much greater as to make the quantity of energy stored in the steam contained in the boiler quite insignificant in comparison with that contained in the water. These facts have been fully illustrated by the figures presented already.

269. The Energy Stored in steam-boilers is capable of very exact computation by the methods already described, and the application of the results there reached gives figures that are quite sufficient to account for the most violently destructive of all recorded cases of explosion.

A steam-boiler is not only an apparatus by means of which the potential energy of chemical affinity is rendered actual and available, but it is also a storage-reservoir, or a magazine, in which a quantity of such energy is temporarily held; and this quantity, always enormous, is directly proportional to the

weight of water and of steam which the boiler at the time contains.

Comparing the energy of water and of steam in the steam-boiler with that of gunpowder, as used in ordnance, it has been found that at high pressures the former become possible rivals of the latter. The energy of gunpowder is somewhat variable, but it has been seen that a cubic foot of heated water, under a pressure of 60 or 70 pounds per square inch, has about the same energy as one pound of gunpowder. The gunpowder exploded has energy sufficient to raise its own weight to a height of nearly 50 miles, while the water has enough to raise its weight about one sixtieth that height. At a low red heat water has about 40 times this latter amount of energy in a form to be so expended. Steam, at 4 atmospheres pressure, yields about one third the energy of an equal weight of gunpowder. At 7 atmospheres it has as much energy as two fifths of its own weight of powder, and at higher pressures its energy increases very slowly.

Below are presented the weights of steam and of water contained in each of the more common forms of steam-boilers, the total and relative amounts of energy confined in each under the usual conditions of working in every-day practice, and their relative destructive power in case of explosion.

In illustration of the results of application of the computations which have been given in § 142, and for the purpose of obtaining some idea of the amount of destructive energy stored in steam-boilers of familiar forms, such as the engineer is constantly called upon to deal with, and such as the public are continually endangered by, the following table has been calculated. This table is made up by Mr. C. A. Carr, U. S. N., from notes of dimensions of boilers designed or managed at various times by the Author, or in other ways having special interest to him. They include nearly all of the forms in common use, and are representative of familiar and ordinary practice.

No. 1 is the common, simple, plain cylindrical boiler. It is often adopted when the cheapness of fuel or the impurity of the water supply renders it unadvisable to use the more com-

TOTAL STORED* ENERGY OF STEAM-BOILERS.

Type.	Area of		Pressure Pounds per Square Inch.	Rated Power. H. P.	Weight of			Stored Energy in (Available)			Energy per pound of		Maximum Height of Projection.		Initial Velocity.	
	G. S.	H. S.			Boiler.	Water	Steam.	Water.	Steam.	Total.	Boiler.	Total W't.	Boiler	Total	Boiler	Total
	Square feet.				Pounds.			Foot-Pounds.			Foot-lbs.		Feet		Feet per sec.	
1 Plain Cylinder........	15	120	100	10	2,500	5,764	11.325	46,605,200	676,698	47,281,898	18 913	5,714	18,913	5,714	1103	606
2 Cornish	36	730	30	60	16,950	2,7471	31.45	57,570,750	709,310	58,260,060	3,431	1,314	3,431	1,314	471	290
3 Two-flue Cylinder....	20	400	150	35	6,775	6,840	37.04	80,572,050	2.377,357	82,949.407	12,243	6,076	12,243	6,076	888	625
4 Plain Tubular........	30	851.97	75	60	9,500	8,255	20.84	50,008,790	1,022,731	51,031,521	5,372	2,871	5,372	2,871	588	430
5 Locomotive	22	1,070	125	525	19,400	5,260	21.67	52,561,075	1,483,896	54,044,971	2,786	2,189	2,786	2,189	423	375
6 "	30	1,350	125	650	25,000	6,920	31.19	69,148,790	2,135,802	71,284.592	2,851	2,231	2,851	2,231	428	379
7 "	20	1,200	125	600	20,565	6,450	25.65	64.452,270	1,766,447	66,218,717	3,219	2,448	3,219	2,448	455	397
8 "	15	875	125	425	14,020	6,330	19.02	64,253,160	1,302,431	65,555,591	4,677	3.213	4,677	3,213	549	455
9 Scotch Marine........	32	768	75	300	2,7045	11,765	29.8	71,272,370	1,462,430	72,734,800	2,689	1,873	2,689	1,873	416	348
10 "	50.5	1,119.5	75	350	37,972	17,730	47.2	107,408,340	2,316,392	109,724,732	2,889	1,968	2,889	1,968	431	356
11 Flue and Return Tubular...... ...	72.5	2,324	30	200	56,000	42,845	69.81	90,531,490	1,570,517	92,101,987	1,644	931	1,644	931	325	245
12 Flue and Return Tubular..........	72	1,755	30	180	56,000	48,570	73.07	102,628,410	1,643,854	104,272,264	1,862	996	1,862	996	346	253
13 Water Tube....... .	70	2,806	100	250	34,450	21,325	35.31	172,455,270	2,108,110	174,563,380	5,067	3,073	5,067	3,073	571	445
14 "	100	3,000	100	250	45,000	28,115	58.5	227,366,000	3,513,830	230,879,830	5,130	3,155	5,130	3,155	575	450
15 "	100	3,000	100	250	54,000	13,410	23.64	108,346,670	1,311,377	109,624,283	2,030	1,626	2,030	1,626	361	323

* This "stored" energy is less than that available in the non-condensing engine by the amount of the latent heat of external work $(p_1 - p_2)v$.

plex, though more efficient, kinds. It is the cheapest and simplest in form of all the boilers. The boiler here taken was designed by the Author many years ago for a mill so situated as to make this the best form for adoption, and for the reasons above given. It is thirty inches in diameter, thirty feet long, and is rated at ten H.P., although such a boiler is often forced up to double that capacity. The boiler weighs a little over a ton, and contains more than twice its weight of water. The water, at a temperature corresponding to that of steam at 100 pounds pressure per square inch, contains over 46,600,000 foot-pounds of available explosive energy, while the steam, which has but one fifth of one per cent of the weight of the water, stores about 700,000 foot-pounds, giving a total of 47,000,000 foot-pounds, nearly, or sufficient to raise one pound nearly 10,000 miles. This is sufficient to throw the boiler 19,000 feet high, or nearly four miles, and with an initial velocity of projection of 1100 feet per second.

Comparing this with the succeeding cases, it is seen that this is the most destructive form of boiler on the whole list. Its simplicity and its strength of form make it an exceedingly safe boiler, so long as it is kept in good order and properly managed; but if, through phenomenal ignorance or recklessness on the part of proprietor or attendant, the boiler is exploded, the consequences are usually exceptionally disastrous.

No. 2 was a "Cornish" boiler designed by the Author, about 1860, and set to be fired under the shell. It was 6 feet by 36, and contained a 36-inch flue. The shell and flue were both of iron $\frac{3}{8}$ inch in thickness. The boiler was tested up to 60 pounds, at which pressure the flue showed some indications of alteration of form. It was strengthened by stay-rings, and the boiler was worked at 30 pounds. The boiler contained about 12 tons of water, weighed itself $7\frac{1}{2}$ tons, and the volume of steam in its steam-space weighed but $31\frac{1}{2}$ pounds. The stored available energies were about 57,600,000 foot-pounds, and about 700,000 of foot-pounds in the water and steam, respectively, a total of nearly 60,000,000. This was sufficient to throw the boiler to the height of 3400 feet, or over three fifths of a mile.

Comparing this with the preceding, it is seen that the intro-

duction of the single flue, of half the diameter of the boiler, and the reduced pressure, have reduced the relative destructive power to but little more than one sixth that of the preceding form.

No. 3 is a "two-flue" or Lancashire boiler, similar in form and in proportions to many in use on the steamboats plying on our Western rivers, and which have acquired a very unenviable reputation by their occasional display of energy when carelessly handled. That here taken in illustration was designed by the Author, 42 inches in diameter, with two 14-inch flues of $\frac{3}{8}$ iron, and is here taken as working at a pressure, as permitted by law, of 150 pounds per square inch. It is rated at 35 horse-power, but such a boiler is often driven far above this figure. The boiler contains about its own weight (3 tons) of water, and but 37 pounds of steam. The stored available energy is 83,000,000 foot-pounds, of which the steam contains but a little above five per cent. Its explosion would uncage sufficient energy to throw the boiler nearly $2\frac{1}{2}$ miles high, with an initial velocity of 900 feet per second. Both this boiler and the plain cylinder are thus seen to have a projectile effect only to be compared to that of ordnance.

No. 4 is the common plain tubular boiler, substantially as designed by the Author at about the same time with those already described. It is a favorite form of boiler, and deservedly so, with all makers and users of shell-boilers. That here taken is 60 inches in diameter, containing 66 3-inch tubes, and is 15 feet long. The specimen here chosen has 850 feet of heating and 30 feet of grate-surface, is rated at 60 horse-power, but is oftener driven up to 75, weighs 9500 pounds, and contains nearly its own weight of water, but only 21 pounds of steam, when under a pressure of 75 pounds per square inch, which is below its safe allowance. It stores 51,000,000 foot-pounds of energy, of which but 4 per cent is in the steam, and this is enough to drive the boiler just about one mile into the air, with an initial velocity of nearly 600 feet per second. The common upright tubular boiler may be classed with No. 4.

Nos. 5–8 are locomotive boilers, of which drawings and

weights were furnished by the builders. They are of different sizes, and both freight and passenger engines. The powers are probably rated low. They range from 15 to 50 square feet in area of grate, and from 875 to 1350 square feet of heating-surface. In weight the range is much less, running from 2½ to a little above 3 tons of water, and from 20 to 30 pounds of steam, assuming all to carry 125 pounds pressure. The boilers are seen to weigh from 2½ to 3 times as much as the water. These proportions differ considerably from those of the stationary boilers which have been already considered. The stored energy averages about 70,000,000 foot-pounds, and the heights and velocities of projection not far from 3000 and 500 feet; although in one case they became nearly one mile and 550 feet, respectively. The total energy is only exceeded, among the stationary boilers, by the two-flued boiler at 150 pounds pressure.

Nos. 9 and 10 are marine boilers of the Scotch or "drum" form. These boilers have come into use by the usual process of selection, with the gradual increase of steam-pressures occurring during the past generation as an accompaniment of the introduction of the compound engine and high ratios of expansion. The selected examples are designed for use in the new vessels of the U. S. Navy. The dimensions are obtained from the Navy Department, as figured by the Chief Draughtsman, Mr. Geo. B. Whiting. The first is that designed for the Nipsic, the second for the Despatch. They are of 300 and 350 horse-power, and contain, respectively, 73,000,000 and 110,000,000 of foot-pounds of available energy, or about 3000 foot-pounds per pound of boiler, and sufficient to give a height and velocity of projection of 3000 and above 400 feet. These boilers are worked at a lower pressure than locomotive boilers; but the pressure is gradually and constantly increasing from decade to decade, and the amount of explosive energy carried in our modern-steam vessels is now enormously greater than that of our locomotives, and in some cases already considerably exceeds that which they would carry were they supplied with boilers of the locomotive type and worked at locomotive pressures. The explosion of the locomotive boiler endangers com-

paratively few lives, and seldom does serious injury to property outside the engine itself. The explosion of one of these marine boilers while at sea would be likely to be destructive of many lives, if not of the vessel itself and all on board.

Nos. 11 and 12 are boilers of the older types, such as are still to be seen in steamboats plying upon the Hudson and other of our rivers, and in New York harbor and bay. No. 11 is a return-tubular boiler having a shell 10 feet in diameter by 23 feet long, 2 furnaces each 7½ feet deep, 8 15-inch and 2 9-inch flues, and 85 return-tubes, 4½ inches by 15 feet. The boiler weighs 25 tons, contains nearly 20 tons of water and 70 pounds of steam, and at 30 pounds pressure stores 92,000,000 foot-pounds of available energy, of which 2½ per cent resides in the steam. This is enough to hoist the boiler one third of a mile with a velocity of projection of 330 feet per second. The second of these two boilers is of the same weight, also of about 200 horse-power, but carries a little more water and steam and stores 104,000,000 foot-pounds of energy, or enough to raise it 1900 feet. This was a return-flue boiler, 33 feet long and having a shell 8¾ feet in diameter, flues 8½ to 15 inches in diameter, according to location.

The "sectional" boilers are here seen to have, for 250 horse-power each, weights ranging from about 35,000 to 55,000 pounds, to contain from 15,000 to 30,000 pounds of water and from 25 to 58 pounds of steam, to store from 110,000,000 to 230,000,000 foot-pounds of energy, equal to from 2000 to 5000 foot-pounds per pound of boiler. The stored available energy is thus usually less than that of any of the other stationary boilers, and not very far from the amount stored, pound for pound, by the plain tubular boiler, the best of the older forms. It is evident that their admitted safety from destructive explosion does not come from this relation, however, but from the division of the contents into small portions, and especially from those details of construction which make it tolerably certain that any rupture shall be local. A violent explosion can only come of the general disruption of a boiler and the liberation at once of large masses of steam and water.

270. The Energy of Steam alone, as stored in the boiler, is given by column 10 of the preceding table. It has been seen that it forms but a small and unimportant fraction of the total stored energy of the boiler. The next table exhibits the effect of this portion of the total energy, if considered as acting alone.

STORED ENERGY IN THE STEAM-SPACE OF BOILERS.

Type.	Total Energy.	Stored in Steam (ft.-lbs.) per lb. of Boiler.	Height of Projection.	Initial Velocity per second.
1. Plain Cylinder	676,693	271	271 ft.	132 ft.
2. Cornish	709,310	42	42 "	32 "
3. Two-flue Cylinder	2,377.357	351	351 "	150 "
4. Plain Tubular	1,022,731	108	108 "	83 "
5. Locomotive	1,483.896	76	76 "	69 "
6. "	2,135,802	85	85 "	74 "
7. "	1,766,447	86	86 "	74 "
8. "	1.302,431	107	107 "	83 "
9. Scotch Marine	1.462.430	54	54 "	59 "
10. "	2,316,392	61	61 "	62 "
11. Flue and Return-tube	1.570,517	28	28 "	42 "
12. " "	1,643.854	29	29 "	43 "
13. Water-tube	2,108,110	61	61 "	59 "
14. "	3.513,830	79	79 "	71 "
15. "	1,311,377	24	24 "	39 "

The study of this table is exceedingly interesting, if made with comparison of the figures already given, and with the facts stated above. It is seen that the height of projection, by the action of steam alone, under the most favorable circumstances, is not only small, insignificant indeed, in comparison with the height due the total stored energy of the boiler, but is probably entirely too small to account for the terrific results of explosions frequently taking place. The figures are those for the stored energy of steam in the working boiler; they may be doubled, or even trebled, for cases of low water; they still remain, however, comparatively insignificant.

The enormous power of molecular forces, even when heat is not added to reinforce them, is illustrated by the often de-

scribed experiments of an artillery officer at Quebec* and others in which a large bombshell is filled with water, safely plugged, and exposed to low temperature. In such cases the expansive force exerted, when freezing, by the formation of ice and the increase of volume accompanying the formation of the crystals, either drives out the plug, sometimes projecting it hundreds of yards (Fig. 123), or actually bursts the thick iron case.

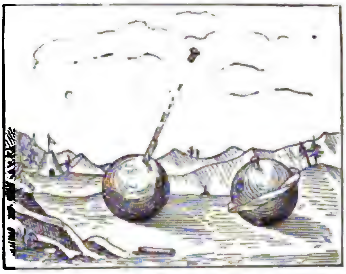

FIG. 123.—EXPANSIVE FORCE OF ICE.

In the more familiar cases of purposely produced explosion, the expansion is caused by the production of great quantities of gas previously in solid form. The violence of the familiar explosives as used in ordnance, in mining operations, is com-

FIG. 124.—AN EXPLOSION.

monly due to this combined effect of heat and chemical action, occurring by the sudden action of powerful forces. In the steam-boiler explosion mighty forces previously long held in subjection finally overcome all resistance, and their sudden application to external bodies constitutes the disaster.

271. Explosion and Bursting are terms which, as often technically used by the engineer, represent radically different phenomena. The explosion of a steam-boiler is a sudden and violent

* Phenomena of Heat. Cazin.

disruption, permitting the stored heat-energy of the enclosed water and steam to be expended in the enormously rapid expansion of its own mass, and, often, in the projection of parts of the boiler in various directions, with such tremendous power as to cause as great destruction of life and property as if the explosion were that of a powder-magazine. The bursting of a boiler is commonly taken to be the rupture, locally, of the structure, by the yielding of its weakest part to a pressure which at the moment may not be deemed excessive, but which is too great for the weakened spot. The collapse of a flue is a form of rupture which is ordinarily considered as of the second class. With high steam-pressure, bursting or the collapse of a flue may occur with a loud report, and may even cause some displacement of the boiler; but it is not generally termed an explosion when the boiler is simply ruptured, and is not torn into separated pieces. There is, however, no real boundary, and the one grades into the other, with no defined line of demarcation.

It occasionally happens that an explosion takes place with such extraordinary violence and destructive effect that it has been thought best, especially by French writers, to class it by itself, and it is denoted a detonant or fulminant explosion, "*explosion fulminante.*" In such cases the report is like that of an enormous piece of ordnance; the boiler is often rent into many parts, or even completely broken up, as if by dynamite; and surrounding objects are destroyed as if by the discharge of a park of artillery.

In any steam-boiler there may at any time exist a state of equilibrium between the resisting power of the boiler and the steam-pressure. In ordinary working, the latter is far within the former; but as time passes the limiting condition is gradually approached, and in every explosion the line is passed. The pressure may rise until the limit of strength is attained, or the resisting power of the boiler may decrease to the limit: in either case the passage of the line is marked by explosion, or a less serious method of yielding.

272. **The Causes of Boiler-explosions** are numerous, but are usually perfectly well understood. Where uncertainty exists,

it is probably the fact that, were the cause ascertained, it would be found to be simple and well known. It is nevertheless true that some authorities, including a few experienced and distinguished members of the engineering profession, believe that there are causes, at once obscure and of great potency and energy, which are not yet satisfactorily understood. In this work the many causes to which explosions are, by various practitioners and writers, attributed may be divided into the known, the probable, the possible, the improbable, and the impossible and absurd.

To the first class belong the general and fairly uniform weakness of boilers as compared with the steam-pressures carried; the sticking of safety-valves, and the thousand and one other causes having their origin in the ignorance, the carelessness, or the utter recklessness of the designer, the builder, or the attendants intrusted with their management. To this class may be assigned the causes of by far the greater proportion of all explosions; and the Author has sometimes questioned whether this category may not cover absolutely all such catastrophes. To the second class may be assigned "low-water," a cause to which it was once customary to attribute nearly all explosions, but which is known to be seldom operative, and so seldom that some authorities now question the possibility of its action at all.* Among the possible causes, acting rarely and under peculiar conditions, the Author would place the overheating of water, and the storage of energy in excess of that in the liquid at the temperature due the existing pressure; the too sudden opening of the throttle-valve or the safety-valve, producing priming and shock; the spheroidal state of water; and perhaps other phenomena. The improbable include the latter, however. The action of electricity—a favorite idea with the uninformed—may be taken as an example of the impossible and absurd. The actual causes of a vast majority of boiler-explosions are now determined by skilled engineers, inspectors, and insurance experts; and it is by them generally supposed that no so-called "mysterious" causes exist, in the sense that they are phenom-

* See opinion of Mr. J. M. Allen, Sibley College Lecture, *Sci. Am. Supplement*, Feb. 19, 1887, p. 9272.

ena beyond the present range of human knowledge and scientific investigation.

All recent authorities agree in attributing boiler-explosions, almost without exception, to one or another of the following general classes of causes, and the Author is inclined to make no exception:

(1) Defective design: resulting in weakness of shell, of flues, or of bracing or staying; in defective circulation; faulty arrangement of parts; inefficiency of provision for supplying water or taking off steam; and defects in arrangement leading to strains by unequal expansions, and other matters over which the designer has control.

(2) Malconstruction: including choice of defective or improper material; faulty workmanship; failure to follow instructions and drawings; omission of stays or braces.

(3) Decay of the structure with time or in consequence of lack of care in its preservation; local defects due to the same cause or to some unobserved or concealed leakage while in operation.

(4) Mismanagement in operation, giving rise to excessive pressure; low water; or the sudden throwing of feed-water on overheated surfaces; or the production of other dangerous conditions; or failure to make sufficiently frequent inspection and test, and thus to keep watch of those defects which grow dangerous with time.

Weakness of boiler or over-pressure of steam are the usual immediate causes of explosions.

It has often been suggested that the most destructive boiler-explosions may be attributable to electricity, and may illustrate the effect of an unfamiliar form of lightning. Such hypotheses are, however, absurd. No storage and concentration of electricity could be produced in a vessel composed of the best of conducting materials and enclosing a mass of fluid incapable of causing electrical currents, either great or small, under the conditions observed in the steam-boiler. The production of electricity seen in Armstrong's experiments, a phenomenon sometimes thought to support this theory, is simply the result of the friction of a moving jet of steam on the nozzle from which

it issued, and presents not the slightest reason for supposing that the electrical hypothesis of the origin of boiler-explosions has any basis of fact.

Professor Faraday, in a report to the British Board of Trade, May, 1859, states his belief in the absurdity of the idea that the water within a steam-boiler may become decomposed, and the explosion of a mixture of gases so produced may burst a boiler: — ". . . . As respects the decomposition of the steam by the heated iron, and the separation of hydrogen, no new danger is incurred. Under extreme circumstances, the hydrogen which could be evolved would be very small in quantity, would not exert greater expansive force than the steam, and would not be able to burn with explosion, and probably not at all, if it, with the steam, escaped through an aperture into the air or even into the fire-place."

Decomposition cannot occur in the steam-boiler, ordinarily; and if it were to happen in consequence of low-water and overheated plates, no oxygen could remain free to explosively combine with it.

A half-century ago, M. Arago, in writing of steam-boiler explosions,* asserted that "no cause of explosion exists which cannot be avoided by means at once simple and within reach of every one." A committee of the Franklin Institute, in 1830, asserted † of boiler-explosions that "they proceed, it is believed, in most cases, from defective machinery, improper arrangement or distribution of parts, or, finally, from carelessness in management." These conclusions are fully justified by all later experience; and it is now admitted by all accepted authorities that a careful examination and study of the facts of the case wili almost invariably enable the experienced engineer to determine the origin of the disaster. It follows that it is perfectly practicable to so design, construct, and manage steam-boilers that there shall be absolutely no danger of explosion.

273. **The Statistics of Explosions** have been very carefully collected for many years in some European countries,

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* Mem. Roy. Acad. Sci. Inst. France, xxi.

† Journal Franklin Institute, 1830.

notably in France, and are now given for the United States in very reliable form by inspectors, governmental and private, who are thoroughly familiar with the subject. The following is a list reported for the year 1885:

CLASSIFIED LIST OF BOILER-EXPLOSIONS.

	January.	February.	March.	April.	May.	June.	July.	August.	September.	October.	November.	December.	Total per class.
Saw-mills and wood-working shops	5	2	4	3	3	2	2	2	3	4	1	2	33
Locomotives	...	4	...	...	...	1	...	...	1	2	1	1	10
Steamboats, tugs, etc.	2	...	2	...	1	1	1	...	...	3	2	4	16
Portables, hoisters, and agricultural engines.	...	...	...	...	1	2	4	2	3	...	2	2	16
Mines, oil wells, collieries, etc.	2	5	3	2	1	1	...	3	...	1	1	1	20
Paper-mills, bleachers, digesters, etc.	1	..	...	...	..	...	1	1	...	...	...	...	3
Rolling-mills and iron-works	1	2	1	. .	...	1	1	1	...	1	...	2	10
Distilleries, breweries, sugar-houses, dye-houses, rendering establishments, etc.	3	1	...	...	3	1	1	...	3	...	4	2	18
Flour-mills and elevators	...	3	1	...	...	2	...	...	1	...	2	1	10
Textile manufactories	...	...	...	...	...	1	...	...	...	...	...	...	1
Miscellaneous	...	3	3	2	2	1	...	...	...	3	2	2	18
Total per month	14	20	14	7	12	12	10	9	11	14	15	17	155
Persons killed—total 220—per month	24	22	20	9	18	14	7	11	11	19	34	31	...
Persons injured—total 288—per month	35	30	28	9	32	6	21	21	13	40	22	21	...

Boilers used in saw-mills are most frequently exploded, presumably because of the cheapness of their construction, and the unskilfulness exhibited in their management; boilers in mines are next in number of casualties. Mill-boilers explode with comparative infrequency. In the United States, according to the best estimates which the Author has been able to make, about one boiler in 10,000 explode among those which are regularly inspected and insured, and ten times that propor-

tion among uninspected and uninsured boilers. In Great Britain, the proportion of explosions is much less than in the United States, the average number being less than one twentieth of one per cent, and the loss of life about three to every two explosions. In Great Britain, as in the United States and elsewhere, the majority of explosions are due to negligence. Explosions might become almost unknown were a proper system of inspection and compulsory repair introduced.

The returns of boiler-explosions in Great Britain and the United States show that not only in number but in destructiveness the record of the United States always exceeds that of Great Britain, as is seen in the following tables:

	No. Explosions.		No. Fatalities.		No. Per's Inj'd.	
	1884.	1885.	1884.	1885.	1884.	1885.
Great Britain .	36	43	24	40	49	62
United States..	152	155	254	220	261	288

	No. Explosions per Million Inhabitants.		No. Fatalities per Explosion.	
	1884.	1885.	1884.	1885.
Great Britain..	1	1.17	.67	.93
United States..	3	3.09	1.67	1.42

The causes of the forty-three explosions in Great Britain are reported to have been:

	Cases.
Deterioration or corrosion of boilers and safety-valves........	20
Defective design or construction of boiler or fittings..........	11
Shortness of water..	4
Ignorance or neglect of attendants..........................	4
Miscellaneous..	4
Total..	43

For the United States there are estimated to have been dangerous cases classified thus:

Causes.	Whole No.	Dangerous.
Deterioration or corrosion of boilers and safety-valves..	17.873	1,727
Defective design or construction of boiler or fittings.....	15,895	2,957
Shortness of water....................................	130	56
Ignorance or neglect of attendants....................	6,404	983
Miscellaneous...	6,928	1,403

The following are two classified lists of defects and causes of dangerous conditions, where in one case over 6000 boilers and in the other above 4000 were inspected in one month:*

CAUSES OF DANGER.

Nature of Defects.	Whole No.	Dangerous.
Deposit of sediment..................................	458	32
Incrustation and scale...............................	630	55
Internal grooving....................................	20	7
Internal corrosion...................................	155	16
External corrosion...................................	346	23
Broken, loose, and defective braces and stays........	205	39
Defective settings...................................	178	17
Furnaces out of shape................................	248	12
Fractured plates.....................................	123	65
Burned plates..	89	22
Blistered plates.....................................	254	11
Cases of defective riveting..........................	1,649	187
Defective heads......................................	30	15
Leakage around tube ends.............................	974	331
Leakage at seams.....................................	574	22
Defective water-gauges	163	27
Defective blow-offs..................................	30	8
Cases of deficiency of water.........................	5	2
Safety-valves overloaded.............................	29	7
Safety-valves defective in construction..............	42	7
Defective pressure gauges............................	238	19
Boilers without pressure-gauges......................	4	0
Defective hand hole plates...........................	3	3
Defective hangers	13	0
Defective fusible plugs..............................	1	0
Total..	6,453	927

* *The Locomotive*, December, 1884; September, 1886.

Nature of Defects.	Whole No.	Dangerous.
Cases of deposit of sediment	516	45
Cases of incrustation and scale	781	54
Cases of internal grooving	28	4
Cases of internal corrosion	173	10
Cases of external corrosion	323	28
Broken and loose braces and stays	50	13
Settings defective	248	17
Furnaces out of shape	179	14
Fractured plates	108	45
Burned plates	100	25
Blistered plates	257	21
Cases of defective riveting	459	49
Defective heads	36	17
Serious leakage around tube ends	461	26
Serious leakage at seams	205	27
Defective water-gauges	161	8
Defective blow-offs	43	8
Cases of deficiency of water	18	6
Safety-valves overloaded	25	6
Safety-valves defective in construction	21	6
Pressure-gauges defective	215	26
Boilers without pressure-gauges	2	2
Total	4,409	457

It is seen that many of these defects, all of which are dangerous and liable to cause explosion, are of very variable frequency; as, for example, defective riveting, which is more than twice as common in the first list as any other defect, but which stands number three in the second; while other defects are of quite regular occurrence, as the presence of sediment and of scale, grooving and other corrosion, injured plates, and defective gauges. Sediment, oxidation, and defective workmanship are evidently the most prolific causes of danger; and unequal expansion, to which many of the reported cases of leakage are attributable, hardly less so.

An inspection of these tables plainly shows that the causes of steam-boiler explosion are commonly perfectly simple, and are well understood; and a person familiar with the subject usually wonders that explosions occur as infrequently as they do, where there are so many sources of danger, and where so little intelligence and care is exhibited in their design, construction, and operation. There are, however, some interesting phenom-

ena and some very ingenious theories as to method of liberation of the enormous stock of energy of which every boiler is a reservoir, to which attention may well be given.

274. **Theories and Methods** of explosions due to other causes than simple increase of steam-pressure or decrease in strength of boiler, and of such accidents as are common and well understood, and produce the greater number of disasters of the class here studied, are as various as they are interesting. The vast majority of all boiler-explosions have been, as has been seen, found to be due to causes which are readily detected, and are the simplest and most obvious possible. Here and there, however, an explosion takes place which is so exceptionally violent or which occurs under such unusual and singular conditions as to give rise to question whether some peculiar phenomenon is not concerned in bringing about so extraordinary a result. Nearly all explosions have been produced either by a gradual rise in pressure until the resisting power of the boiler has been exceeded and an extended rupture liberates the stored energy; or by a gradual reduction of the strength of the structure, until at last it is insufficient to withstand the ordinary working pressure, and a general yielding leads to the same result. Such cases require little comment and no explanation; but the rare instances in which a sudden development of forces far in excess of those exhibited in regular working have been believed to have been observed have given rise to much speculation, to many ingenious theories, and to an immense amount of speculation and misconception on the part of those who are unfamiliar with science, and without experience in the operation of this class of apparatus.

Explosions probably always occur from perfectly simple and easily comprehended causes, are always the result of either ignorance or carelessness, and are always preventable where intelligence and conscientiousness govern the design, the construction, and the management of the boiler. A well-designed boiler, properly proportioned for its work and to carry the working pressure, well built, of good material, and intelligently and carefully handled, has probably never been known to explode. Explosions probably never occur, with either a grad-

ually increasing pressure of steam or decreasing strength of boiler, unless the strength of the structure is quite uniform; local weakness is a safety-valve which permits a "burst," and insures against that more general disruption which is called an "explosion." A long line of weakened seam, an extended crack, or a considerable area of surface thinned by corrosion may lead to an explosion and a general breaking up of the whole apparatus; but any minor defect, where its site is surrounded by strong parts, will not be likely to produce that result.

The Method of Explosion is in the great majority of cases the opening of a small orifice at a point of minimum strength, with outrush of water or steam, or both; the rapid extension of the rupture until it becomes so great and the operation is so sudden that, no time being given for the gradual discharge of the enclosed fluids, the boiler is torn violently apart by the internal unrelieved pressure and distributed in pieces, the number of which is determined by the character and extent of the lines or areas of weakness.

275. **Clark and Colburn's Theory** of boiler-explosions has been accepted as a "working hypothesis" by many engineers, and has some apparent foundation in experimentally ascertained fact. This theory is attributed to Mr. Zerah Colburn;* but was probably, as stated by Mr. Colburn himself, original with Mr. D. K. Clark, who suggests that a rupture initiated at the weakest part of a boiler, above or near the water-line, may be extended, and an explosion precipitated by the impact of a mass of water carried toward it by the sudden outrush of a large quantity of steam, precisely as the "water-hammer" observed so frequently in steam-pipes causes an occasional rupture of even a sound and strong pipe. In fact, many instances have been observed in which the rent thus presumed to have been produced has extended not only along lines of reduced section, but through solid iron of full thickness and of the best quality. It is thus that Mr. Clark would account for the shat-

* Steam-boiler Explosions. Zerah Colburn. London: John Weale. 1860.

tering and the deformation of portions of the disrupted boiler, which are often the most striking and remarkable phenomena seen in such cases.

Colburn suggests that the explosion, in such cases, although seemingly instantaneous, may actually be a succession of operations, three or four at least, as the following:

(1) The initial rupture under a pressure which may be and probably often is the regular working pressure; or it may be an accidentally produced higher pressure; the break taking place in or so near the steam-space that an immediate and extremely rapid discharge of steam and water may occur.

(2) A consequent reduction of pressure in the boiler and so rapid that it may become considerable before the inertia of the mass of water will permit its movement.

(3) The sudden formation of steam in great quantity within the water, and the precipitation of heavy masses of water, with this steam, toward the opening, impinging upon adjacent parts of the boiler and breaking it open, causing large openings or extended rents.

(4) The completion of the vaporization of the now liberated mass of water to such extent as the reduction of the temperature may permit, and the expansion of the steam so formed, projecting the detached parts to distance depending on the extent and rapidity of this action.

This series of phenomena may evidently be the accompaniment of any explosion, to whatever cause the initial rupture may be due. One circumstance lending probability to this theory is the rarity of explosions originating in the failure of "water-legs" or other parts situated far below the water-line. This occasionally happens, as was seen some time ago at Pittsburg in the explosion of a vertical boiler caused by a crack in the water-leg; but it is almost invariably observed that explosions occur where long lines of weakened metal, defective seams, or of "grooving" extend nearly or quite to the steam-space.* A local defect well below the water-line would

* The Westfield explosion illustrates this case. Jour. Frank Inst. 1875.

usually simply act as a safety-valve, discharging the contents of the boiler without explosion.

276. Corroboratory Evidence has been here and there found. Lawson's experiments, and those of others, as well as many accidental explosions, have supplied evidence somewhat but not absolutely corroboratory of the Clark and Colburn theory. Mr. D. T. Lawson having become convinced of the truth of the Clark and Colburn theory, further conceived the idea that the opening and sudden closing of the throttle or the safety-valve might cause precisely the same succession of phenomena, and lead to the explosion of boilers, the opening starting the current and the closing of the valve producing impact that may disrupt the boiler. To test the truth of his hypothesis, he made a number of experiments, and succeeded in exploding a new and strong boiler at a pressure far below that which it had immediately before safely borne. As a preventive, he proposed the introduction of a perforated sheet-iron diaphragm dividing the interior of the boiler at or near the water-line; the expectation being that it would check the action described by Colburn and prevent that percussive effect to which explosion was attributed by him, and also that it would be found to possess some other advantages.

The experiments were made at Munhall, near Pittsburg, Pa., in March, 1882, the boiler being of the cylindrical variety, 30 inches (76 cm.) in diameter and $6\frac{3}{4}$ feet (2.06 m.) in length, of iron $\frac{3}{16}$ inch (0.48 cm.) in thickness. Its strength was estimated at 430 pounds per square inch ($28\frac{5}{8}$ atmos.). It was fitted with a diaphragm, as above described.

After some preliminary tests, the following were made,* the valve being opened at intervals and suddenly closed again at the pressures given below, as taken from the log. A steam-gauge was attached to the boiler above and one below the diaphragm. The boiler contained 18 inches of water. Steam was generated slowly, and when the pressure had reached 50 pounds operating the discharge valve began with the following results:

* Report of U. S. Inspectors to the Secretary of the Treasury, March 23, 1882.

Steam-pressure at which Discharge-valve was raised.	Steam-gauge above Diaphragm.		Steam-gauge below the Diaphragm.	
	Needle fell below	Needle rose above	Needle fell below	Needle rose above
Pounds.	Pounds.	Pounds.	Pounds.	Pounds.
50	7	3	3	00
80	10	7	4	00
100	12	7	5	3
125	15	15	8	4
150	20	20	8	7
175	15	23	10	10
200	20	20	15	00
225	30	20	12	00
230	40	30	10	00
250	25	20	10	00
275	30	25	15	00
300	40	35	15	00

When the pressure in the boiler reached 300 pounds to the square inch it was decided that the boiler had been sufficiently tested, and the boiler was emptied and inspected. The rivets, seams, and all the other parts of the boiler were examined, and no strain, rupture, or weakness was discovered. The diaphragm was then cut out, leaving the flanges riveted to the sides of the shell and across the heads. The boiler was then again tested with the following results:

Steam-pressure at which Discharge-valve was raised.	Steam-gauge attached to the Boiler in the Steam-space.		Steam-gauge attached to Boiler in Water-space.	
	Needle fell below	Needle rose above	Needle fell below	Needle rose above
Pounds.	Pounds.	Pounds.	Pounds.	Pounds.
100	3	00	3	00
125	2	00	3	00
150	5	00	5	00
175	4	2	3	2
200	5	00	5	00
210	3	00	3	00
225	5	00	3	00
235	Exploded.			

When the discharge-valve was opened at 235 pounds pressure it caused the explosion of the boiler. It was blown into frag-

ments. The iron was torn and twisted into every conceivable shape; strips of various sizes and proportions were found in all directions. The boiler did not always tear at the seams, but principally in the solid parts of the iron. At the time of the explosion the water-line was higher than during the test immediately preceding. At an earlier privately made experiment, as reported by the same investigator, an explosion of a new boiler had been similarly produced at one half the pressure which it had been estimated that the boiler might sustain. A significant fact exhibited in the record is the enormously greater fluctuation of pressure in the boiler during the first than during the second trial, and the difference in the amount of that fluctuation above and below the diaphragm.

The result of this action in the ordinary operation of the safety-valve or of the throttle-valve is apparently extremely uncertain. Many explosions have occurred under such circumstances as would seem to indicate the probability of the action above described having been their cause, the disaster following the opening of safety-valves, or of the throttle at starting the engine.

On the other hand, these operations are of constant occurrence, and with weak and dangerous boilers, yet such explosions are known to be extremely rare. The Author, while officially engaged in attempting the experimental production of boiler-explosions, as a member of the U. S. Board appointed for that purpose, made numerous experiments of this nature, but never succeeded in producing an explosion. The danger would seem to be, fortunately, less than it might be, judged from the above. The introduction of feed-water into the steam-space of boilers, producing sudden removal of pressure from the surface of the water, is sometimes supposed to have caused explosions. The explosion of a battery of several boilers simultaneously—not an infrequent case—is supposed to be attributable to the action described above, following the rupture of some one of the set.

That this action can have more than a slight effect, and that it can do more than accelerate the rupture of a weak boiler and

intensify the effects of explosions due to the action of other phenomena, remains to be proven by further investigation.

Mr. J. G. Heaffman, writing in 1867,* anticipated Mr. Lawson's idea, and, after describing an explosion of a bleaching-boiler, to which the steam was supplied from a separate steam-boiler, attributes the catastrophe to impact of water against the shell on the accidental production of an opening at the man-hole, and asserts that explosions thus occur, not only from excess of pressure, but also from shock. He further states that, in accordance with a request made by the Association of German Engineers, a commission of the Breslau Association, experimenting with a small glass boiler, found that when the escape-pipes are only gradually opened, and the steam allowed gradually to escape, the generation of steam quietly continues and the water remains tranquil. But if the valve is quickly opened, steam-bubbles suddenly form all through the water, and rising to the surface, produce violent commotion. In one of these experiments it was his duty to watch the manometer, while another person quickly opened the valve to allow the steam to escape. As soon as the valve was opened the pressure fell 3 pounds, but immediately again began to rise, and the boiler exploded. Where it had been in contact with the water it was shattered to powder, which lay around like fine sand. Of the entire boiler only a few small pieces of the size of a dollar were left. Afterwards they constructed a similar glass boiler, with a cylinder 7 inches in diameter and 9 inches in length, and to the ends metal heads were fastened; in the heads were pipes for leading in the steam. By means of a force-pump the boiler was filled with boiling water, the valve being left open meanwhile, in order that its sides might become evenly heated. Then half the water was drawn off, and air let in, and afterwards more boiling water forced in, so that the air was compressed, until the boiler exploded at a pressure of 15 atmospheres.

The report was not nearly as loud as at the former explosion, which took place at a pressure of only three atmospheres,

* Journal of Assoc. of German Engineers, 1867; *Iron Age*, 1867.

and the glass was only broken into several pieces. This, Mr. Heaffman considers, proves that the action of the water on the boiler is such as would be produced by exploding nitro-glycerine in the water. He goes on to state that in bleacheries, dye-works, etc., the habit often prevails of suddenly opening the steam-cocks, thus endangering the boiler.

He does not assert that every time a cock is suddenly opened an explosion *must* follow; but that it *may* take place, experience has shown. In the experiments above described they had many times opened the glass boiler without causing an explosion; with the second boiler, too, they had done so without being able to bring about explosion, both with high and low pressure. In the former class of explosions the steam shatters, twists, and contorts everything in an instant.

"*Water-hammer*" has, by the bursting of steam-pipes, by a process somewhat closely related to that described by Clark and Colburn, sometimes caused fatal injury to those near at the instant of the accident. This is a phenomenon which has long been familiar to engineers, and the author has been cognizant of many illustrations, in his own experience, of its remarkable effects, and has sometimes known of almost as serious losses of life as from boiler-explosions. It is rarely the cause of serious loss of property.

When a pipe contains steam under pressure, and has introduced into it a body of cold water, or when a cold pipe containing water is suddenly filled with steam, the contact of the two fluids, even when the water is in very small quantities, results in a sudden condensation which is accompanied by the impact of the liquid upon the pipe with such violence as often to cause observable or even very heavy shocks; and often a succession of such blows is heard, the intensity of which is the greater as the pipe is heavier and larger, and which may be startling, and even very dangerous. It is not known precisely how this action takes place; but the Author has suggested the following as a possible outline of this succession of phenomena:*

* "Water-hammer in Steam-pipes." Trans. Am. Soc. Mech. Engrs., vol. iv. p. 404.

The steam, at entrance, passes over or comes in contact with the surface of the cold water standing in the pipe. Condensation occurs, at first very slowly, but presently more quickly, and then so rapidly that the surface is broken, and condensation is completed with such suddenness that a vacuum is produced. The water adjacent to this vacuum is next projected violently into the vacuous space, and, filling it, strikes on the metal surfaces and with a blow like that of a solid body, the liquid being as incompressible as a solid. The intensity of the resulting pressure is the greater as the distance through which the surface attacked can yield is the less, and enormous pressures are thus attained, causing the leakage of joints, and even the straining, twisting, and bursting of pipes. In some cases the whole of an extensive line or system of pipes has been observed to writhe and jump to such extent as to cause well-grounded apprehension.

The Author once had occasion to test the strength of pipes which had been thus already burst. They were 8 inches in diameter (20.32 cm.), and of a thickness of $\frac{3}{8}$ inch (0.95 cm.), and had been, when new, subjected to a pressure of about 20 atmospheres (300 lbs. per sq. in.). When tested by the Author in their injured condition they bore from one third more to nearly four times as high pressures before the cracks which had been produced were extended. It is perhaps not absolutely certain that some of these pieces of pipe may not have been cracked at lower pressures than the above; but it is hardly probable. It seems to the Author very certain that the pressures attained in his tests were approximately those due to the water-hammer, or were lower. The steam-pressure had never exceeded about four atmospheres (60 lbs. per sq. in.).

It is evident that it is not safe, in such cases, to calculate simply on a safe strength based on the proposed steam-pressures; but the engineer may find those actually met with enormously in excess of boiler-pressure, and a "factor-of-safety" of 20 may prove too small, it being found, as above, that the water-hammer may produce local pressure approaching, if not exceeding, 70 atmospheres (1000 lbs. per sq. in.). These facts,

now well ascertained and admitted, lend some confirmation to the Clark and Colburn theory of explosions.

277. Energy Stored in Heated Metal is vastly less in amount, with the same range of temperature, than in water. The specific heat of iron is but about one ninth that of water, and the weight of metal liable to become overheated in any boiler is usually small. If the whole crown-sheet of a locomotive-boiler were to be heated to a full red heat, it would only store about as much heat per degree as forty pounds (18 kgs.) of water, or not far from 30,000 thermal units (7560 calories), or 23,160,000 foot-pounds (3,330,000 kilog.-m., nearly), or about three tenths of the total energy of the fluids concerned in the explosion. It would be sufficient, however, to considerably increase the quantity of steam present in the steam-space; and this increase, if suddenly produced, and too quickly for the prompt action of the safety-valve, might evidently precipitate an explosion, which would be measured in its effects by the total energy present.

It thus becomes at once obvious that the danger from the presence of this stock of excess energy is determined not only by the weight of metal heated and its temperature, but even more by the rate at which that surplus heat is communicated to the water that may be brought in contact with it, by pumping in feed-water, or by any cause producing violent ebullition. It is probable that this cause has sometimes operated to produce explosions; but oftener that the loss of strength produced by overheating is the more serious source of danger. It is also evident that the first is the more dangerous as the pressures are lower, the second with high pressures.

As illustrating a calculation in detail, assume $\left\{\begin{matrix}\text{2.4 sq. metres}\\ \text{25 sq. feet}\end{matrix}\right\}$ of crown-sheet, or boiler-shell, overheated $\left\{\begin{matrix}556^\circ \text{ C.}\\ 1000^\circ \text{ F.}\end{matrix}\right\}$, the metal being $\left\{\begin{matrix}\text{0.95 centimetres}\\ \tfrac{3}{8}\text{ inch}\end{matrix}\right\}$ in thickness, and its total weight $\left\{\begin{matrix}\text{170 kilogs.}\\ \text{375 pounds}\end{matrix}\right\}$. Then the product of weight into range of temperature, into specific heat (0.111), is the measure of the heat-energy stored.

$$375 \times 1000 \times 0.111 = 41{,}625 \text{ B. T. U., nearly;}$$
$$170 \times 556 \times 0.111 = 10{,}492 \text{ calories, nearly;}$$

and in mechanical units,

$$41{,}625 \times 772 = 32{,}134{,}500 \text{ foot-pounds nearly;}$$
$$10{,}502 \times 423.55 = 4{,}443{,}886 \text{ kilog.-metres nearly;}$$

which is fifteen or twenty times the energy stored in the steam in a locomotive-boiler in its normal condition, and about one half as much as ordinarily exists in water and steam together. It is evident that the limit to the destructiveness of explosions so caused is the rate of transfer of this energy to the water thrown over the hot plate, and the promptness with which the steam made can be liberated at the safety-valve. A sudden dash of water or spray over the whole of such a surface might be expected to even produce a "fulminating" explosion. Fortunately, as experience has shown, so sudden a transfer or so complete a development of energy rarely, perhaps never, takes place.

278. **The Strength of Heated Metal** is known usually to decrease gradually with rise in temperature, until, as the welding or the melting-point, as the case may be, is approached, it becomes incapable of sustaining loads. Both iron and steel, however, lose much of their tenacity at a bright-red heat, at which point they have less than one fourth that at ordinary temperatures. A steam-boiler in which any part of the furnace is left unprotected by the falling of the water-level is very likely to yield to the pressure, and an explosion may result from simple weakness. At temperatures well below the red heat this will not happen.

279. **"Low Water,"** in consequence of the obvious dangers which attend it, and the not infrequent narrow escapes which have been known, has often been by experienced engineers considered to be the most common, even the almost invariable, cause of explosions. This view is now refuted by statistics and a more extended observation and experience; but it remains one of the undeniable sources of danger and causes of accident.

Its origin is usually in some accidental interruption of the

supply of feed-water; less often an unobserved leak or accelerated production of steam. Whatever the cause, the result is the uncovering of those portions of the heating-surface which are highest, and their exposure, unprotected by any efficient cooling agency, to the heat of the gases passing through the flue at that point. Should it be the case of a locomotive or other boiler having the crown-sheet of its furnace so placed as to be first exposed when the water-level falls, the iron may become heated to a full red heat; if the highest surfaces are those of tubes, through which gases approximating the chimney in temperature are passing, the heat and the danger are less. In either case danger is incurred only when the temperature becomes such as to soften the iron, or when the return of the water with considerable rapidity gives rise to the production of steam too rapidly to be relieved by the safety-valve or other outlet. Such explosions probably very seldom actually occur, even when all conditions seem favorable. Every boiler-making establishment is continually collecting illustrations of the fact that a sheet may be overheated, and may even alter its form seriously when overheated, without completely yielding to pressure; and the Author has taken part in many attempts to experimentally produce explosions by pumping feed-water into red-hot boilers, and has but once seen a successful experiment. The same operation, in the regular workings of boilers, has been often performed by ignorant or reckless attendants without other disaster than injury to the boiler, but it has unquestionably on other occasions caused terrible loss of life and property. The raising of a safety-valve on a boiler in which the water is low, by producing a greater violence of ebullition in the water on all sides the overheated part, may throw a flood of solid water or of spray over it; and it is probable that this has been a cause of many explosions. The Author has seen but a single explosion produced in this way, although he has often attempted to so produce such a result. In three experiments on a plain cylindrical boiler, empty and heated to the red heat, the result of rapidly pumping in a large quantity of water was in the first the production of a vacuum, in the second an excess of pressure safely and easily

relieved by the safety-valve, and in the third case a violent explosion of the boiler and the complete destruction of the brick masonry of its setting.* A committee of the Franklin Institute, conducting similar experiments,† had the same experience, the pressure "rising from one to twelve atmospheres within two minutes" after starting the pump. The most rapid vaporization occurs, as is well known, at a comparatively low temperature of metal; at high temperature the spheroidal condition is produced, and no contact exists between metal and liquid.

Mr. C. A. Davis, President of the New York and Boston Steamboat Co., in a letter addressed, Dec. 7, 1831, to the Collector of the Port of New York, and answering inquiries of the United States Treasury Department, wrote:‡

"I have noted that by far the greatest number of accidents by explosion and collapsing of boilers and flues—I might say seven tenths—have occurred either while the boat was at rest, or immediately on starting, particularly after temporary stoppages to take in or land passengers. These accidents may occur from directly opposite causes—either by *not letting off enough steam, or by letting off too much:* the latter is by far the most destructive."

The idea of this writer was that the "letting off of too much" steam, producing low-water, was the most frequent cause of explosions—an idea which has never since been lost sight of.

The chief-engineer of the Manchester (G. B.) Steam-boiler Association, in 1866–67, repeatedly injected water into overheated steam-boilers, but never succeeded in producing an explosion.§ Yet, as has been seen, such explosions may occur.

A writer in the Journal of the Franklin Institute,‖ a half-century or more ago, asserted that "the most dreadful accidents from explosions which have taken place have occurred from low-pressure boilers." It was, as he states, "a fact that more persons had been killed by low than by high pressure boilers."

* *Sci. Am.*, Sept. 1875.

† Jour. Franklin Inst. 1837, vol. xvii.

‡ Report on Steam-boilers, H. R., 1832.

§ *Mechanics' Magazine*, May, 1867.

‖ Vol. iii. pp 335, 418, 420.

Nearly all writers of that time attributed violent explosions to low-water, and some likened the phenomenon to that observed when the blacksmith strikes with a moist hammer on hot iron.

Thus, if the boiler is strong, and built of good iron, and not too much overheated, or if the feed-water is introduced slowly enough, it is possible that it may not be exploded; but with weaker iron, a higher temperature, or a more rapid development of steam, explosion may occur. Or, if the metal be seriously weakened by the heat, the boiler may give way at the ordinary or a lower pressure; which result may also be precipitated by the strains due to irregular changes of dimensions accompanying rapid and great changes of temperature.

Explosions due to low-water, when there is a considerable mass of water below the level of the overheated metal, are sometimes fearfully violent; a boiler completely emptied of water, and only exploded by the volume of steam contained within it, is far less dangerous. Low-water and red-hot metal in a locomotive or other firebox boiler are for this reason far more dangerous than in a plain cylindrical boiler, since, as was indicated by the experiments conducted by the Author, the latter must be entirely deprived of water before this dangerous condition can arise. In the course of the numerous experiments already alluded to, many attempts were made to overheat the latter class of boiler; but none were successful until the water was entirely expelled. Experiments with apparatus devised for the purpose of keeping the steam moist under all circumstances indicate that it is difficult if not impossible to overheat even an uncovered firebox crown-sheet if the steam be kept moist, and that such steam is very nearly as good a cooling medium, in such cases, as the water itself.

Fig. 125* represents a boiler exploded by the introduction of water after it had been emptied by carelessly leaving open the blow-cock. This boiler was about five years old; and the explosion, as is usual in such cases, was not violent, the small amount of water entering and the weakness of the sheet conspiring to prevent the production of very high pressure or the

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* *The Locomotive*, Sept. 1886, p. 129.

storage of much energy. The whole of the lower part of the shell of the boiler was found, on subsequent examination, to have been greatly overheated. One man was killed by the falling of the setting upon him; no other damage was done.

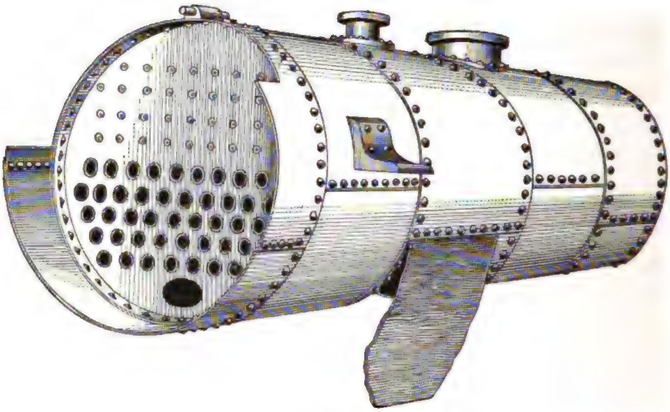

FIG. 125.—BOILER EXPLODED. CAUSE, LOW-WATER.

Fig. 126 shows the effect of a similar operation on a water-tube boiler. The feed-water was cut off, and not noticed until the water-level became so low that the boiler was nearly empty and the tubes were overheated. One of the tubes burst, and the damage was speedily repaired at a cost of $15, and the works were running the next day.*

FIG. 126.—TUBE BURST: LOW-WATER.

That low-water and the consequent overheating of the boiler does not necessarily produce disaster, even when the water is again supplied before cooling off, was shown as early as 1811, by the experience of Captain E. S. Bunker of the Messrs. Stevens' steamboat Hope, then plying between New York and Albany. During one of the regular passages he discovered that the water had been allowed by an intoxicated fireman to completely leave both the boilers. He at once started the pump, and, filling up the boilers, proceeded on his way, no other sign of danger presenting itself than "a crackling in the

* G. H. Babcock.

boiler as the water met the hot iron, the sound of which was like that often heard in a blacksmith's shop when water is thrown on a piece of hot iron." * A year later Captain Bunker repeated this experience at Philadelphia on the Phœnix, where the boilers were of the same number and size as those of the Hope.†

Defective circulation may cause the formation of a volume of steam in contact with a *submerged* portion of the heating-surface. The Author, when in charge of naval boilers during the civil war, 1861–5, found it possible on frequent occasions to draw a considerable volume of practically dry steam from the water-space between the upper parts of two adjacent furnaces at a point two or three feet below the surface-water level. After drawing off steam for a few seconds, through a cock provided to supply hot water for the engine and fire-rooms, water would follow as in the normal condition of the boiler. This condition often occurs in some forms of boiler, and has been occasionally observed by every experienced engineer. It would not seem impossible, therefore, that steam might be sometimes thus encaged in contact with the furnace, and thus cause overheating of the adjacent metal. Many such instances have been related; but they have been commonly regarded by the inexperienced as somewhat apocryphal.‡

In order that the danger of overheating the crown-sheet of the locomotive type of boiler may be lessened, it is very usual to set it lower at the firebox end, when employed as a stationary boiler, so as to give a greater depth of water over the crown-sheet than over the tubes at the rear. The plan of giving greatest depth of water, when possible, at that end of the boiler at which the heating-surfaces near the water-surface are hottest is always a good one.

Mr. Fletcher concluded from his experiments that low-water is only a cause of danger by weaking the overheated plates. He says: §

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* Doc. No. 21, H. R., 25th Congress, 3d Session, 1838, p. 103.

† Ibid.

‡ See *London Engineer*, Dec. 7, 1860, pp. 371, 403.

§ *London Engineer*, Mar. 15, 1867, p. 228.

"These experiments, it is thought, may be accepted as conclusive that the idea of an explosion arising from the instantaneous generation of a large amount of steam through the injection of water on hot plates is a fallacy."

The conclusion of the Author, in view of the experiments of the committee of the Franklin Institute and of his own personal experience in the actual production of explosions by this very process, as elsewhere described, does not accord with the above; but it is sufficiently well established that low-water may frequently occur and feed-water may be thrown upon the overheated plates without necessarily causing explosion. Danger does, however, unquestionably arise, and such explosions have most certainly occurred—possibly many in the aggregate.

Low-water is certainly very rarely, perhaps almost never, the cause of explosion of other than firebox boilers; in these, however, the danger of overheating the crown-sheet of the furnace, if the supply of water fails, is very great, and in such cases explosion is always to be feared. The most disastrous explosions are usually those, however, in which the supply of water is most ample.

280. **Sediment and Incrustation** sometimes produce the effect of low-water in boilers, even where the surfaces affected are far below the surface of the water. Every increase of resistance to the passage of heat through the metal and the incrusting layer of sediment or scale causes an increase of temperature in the metal adjacent to the flame or hot gases, until, finally, the incrustation attaining a certain thickness, the iron or steel of the boiler becomes very nearly as hot as the gases heating it. Should this action continue until a red heat, or a white heat even, as sometimes actually occurs, is reached, the resistance becomes so greatly reduced that the sheet yields, and either assumes the form of a "pocket" or depression, as often happens with good iron or with steel, or it cracks, or it even opens sufficiently to cause an explosion. "Pockets" often form gradually, increasing in extent and depth day by day, until they are discovered, cut out, and a patch or a new sheet put in, or until rupture takes place. In such cases the

incrustation keeps the place covered while permitting just water enough to pass in to cause the extension of the defect.

In some cases the process is a different and a more disastrous one: The scale covers an extended area, permitting it to attain a high temperature. After a time a crack is produced in the scale by the unequal expansion of the two substances and the inextensibility of the incrustation; and water entering through this crack is exploded into steam, ripping off a wide area of incrustation previously covering the overheated sheet, and giving rise instantly, probably, to an explosion which drives the sheet down into the fire, and may also rend the boiler into pieces, destroying life and property on every side. Such an explosion usually takes place with the boiler full of water and its stored energy a maximum, and the result is correspondingly disastrous.

Certain greasy incrustations and some floury forms of mineral or vegetable deposits have been found peculiarly dangerous, as, in even exceedingly thin layers, they are such perfect non-conductors as to speedily cause overheating, strains, cracks, leakage, and often explosion. M. Arago mentions a case in which rupture occurred in consequence of the presence of a rag lying on the bottom of a boiler.*

The effect of incrustation in causing the overheating of the fire-surfaces, the formation of a "pocket" and final rupture, is well shown in the illustrations which follow.

When the water is fully up to the safe level, as at the right in the first of the two figures, the heat received from the furnace-gases is promptly carried away by the water, and the sheet is kept cool. When the water falls below that level, or is prevented by incrustation from touching the metal, as in the left-hand illustration, the sheet becomes red-hot, soft, and weak, and yields as shown. When this goes on to a sufficient extent,

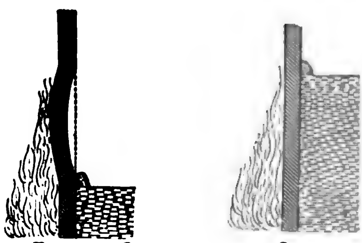

FIG. 127.—OVERHEATING THE SHEET.

* Report of the Committee of the Franklin Institute.

as on a horizontal surface (Fig. 128), a pocket is produced. The illustration represents a sheet removed from the shell of an externally fired boiler thus injured.

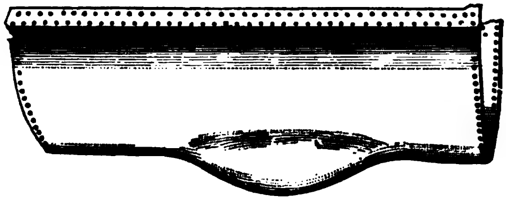

FIG. 128.—A "POCKET."

Finally, when the defect is not observed and the injured sheet removed, the metal may finally give way entirely, per-

FIG. 129.—RUPTURED POCKET.

mitting the steam and water to issue, as in the last illustration of the series, in which this last step in the process is well represented. Where the area thus affected is considerable,

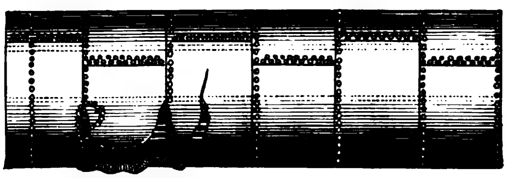

FIG. 130.—SHELL RUPTURED.

the result may be a general breaking up of that portion of the shell, as in the next figure, and an explosion may prove to be the final step in the chain of phenomena described. In other cases, where, as in the next sketch, a line of weakness may be

the result of other causes, a large section of the boiler may be broken out, as at *AD*, Fig. 131.

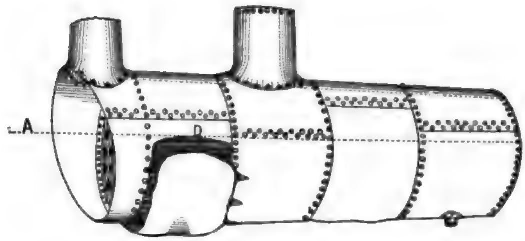

FIG. 131.—EXTENDED RUPTURE.

The deposition of sediment and of scale takes place not only in the boiler, but also with some kinds of water, in the feed-pipe, as is illustrated in the accompanying engraving, which is made from an actual case in which the pipe was so nearly filled as to become quite incapable of performing its office. A current has apparently no effect, in many such cases, in preventing the deposition of scale.

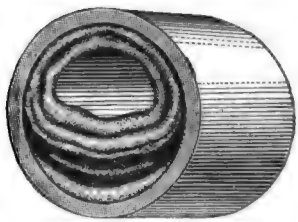

FIG. 132.—INCRUSTATION IN FEED-PIPE.

The Author has known hard scale to form in the cones of a Giffard injector under his charge, where the stream was moving with enormous velocity, and loudly *whistling* as it passed.

Instances are well known of the explosion, with fatal effect, of *open vessels*, in consequence of the action above described. Mr. G. Gurney in 1831 gave an account of such an explosion of the water in an open caldron, at Meux's brewery, by which one person was killed and several others injured.* It was found that the bottom had become incrusted with sediment, and the sudden rupture of the film, permitting contact of the water above with the overheated metal below, caused such a sudden and violent production of steam that it actually ruptured the vessel. The process of which this is an illustration is precisely analogous to suddenly throwing feed-water into an overheated boiler.

* Report on Steam Carriages. Doc. 101, 22d Congress, 1st Session, p. 31.

281. Energy stored in Superheated Water has been sometimes considered a source of danger to steam-boilers and a probable cause of explosions. The magnitude of this stock of energy is not likely to differ greatly from that of water at the same temperature under the pressure due that temperature, and for present purposes specific heat may be taken as unity. The quantity of heat so stored is therefore measured very nearly by the product of the weight of water so overheated, the mean range of superheating, and the specific heat here taken as unity. It is not known how large a part of the water in any boiler can be superheated, or the extent to which this action can occur. It is often doubted, however, whether it can take place at all in steam-boilers.

This condition occurring, the experiments of MM. Donny, Dufour, and others show that the larger the mass of water the less the degree of superheating attainable; the more impure the water, or the greater the departure from the condition of distilled water, and the larger the proportion of air or sediment mechanically suspended, the more difficult is it to attain any considerable superheating.

As early as 1812,* Gay-Lussac observed a retardation of ebullition in glass vessels; thirty years later,† M. Marcet found that water deprived of air can be raised several degrees above its normal boiling-point; while Donny,‡ Dufour,§ Magnus,‖ and Grove¶ all succeeded in developing this phenomenon more or less remarkably. Donny, sealing up water deprived of air in glass tubes, succeeded in raising the boiling point to 138° C. (280° F.), at which temperature vaporization finally occurred explosively. Dufour, by floating globules of pure water in a mixture of oils of density equal to that of the water, succeeded *with very minute* globules in raising the boiling-point to 175° C. (347° F.), at which temperature the normal tension of its

* Ann. de Chimie et de Physique, lxxxii.
† Bibl. Univ. xxxviii.
‡ Ann. de Ch. et de Phys., 3me serie, xvi.
§ Bibl. Univ., Nov. 1861, t. xii.
‖ Poggendorff's Ann. t. cxiv.
¶ Cosmos, 1863.

steam is 115 pounds per square inch (nearly eight atmospheres) by gauge. In such cases the touch of any solid or of bubbles of gas would produce explosive evaporation. Solutions always boil at temperatures somewhat exceeding the boiling-point of water, but usually quietly and steadily. In all these cases the rise in temperature seems to have been the greater the smaller the mass of water experimented with.

In all ordinary cases of steam-boiler operation the mass of water is simply enormous as compared with the quantities employed in the above-described laboratory experiments; the water is almost never pure, and probably as invariably contains more or less air. It would seem very unlikely that such superheating could ever occur in practice. There is, however, some evidence indicating that it may.

Mr. Wm. Radley* reports experimenting with small laboratory boilers of the plain cylindrical form, and continuing slowly heating them many hours, finally attaining temperatures exceeding the normal by 15° F. (8°.3 C.). The investigator concludes:

"Here we have conclusive data suggesting certain rules to be vigorously adopted by all connected with steam-boilers who would avoid mysterious explosions: First, never feed one or more boilers with surplus water that has been boiled a long time in another boiler, but feed each separately. Second, when boilers working singly or fed singly are accustomed, under high pressure, to be worked for a number of hours consecutively, day and night, they should be completely emptied of water at least once every week, and filled with fresh water. Third, in the winter season the feed-water of the boiler should be supplied from a running stream or well; thaw water should never be used as feed for a boiler."

"Locomotive, steamboat, and stationary engine boilers have their fires frequently *banked up* for hours, without feeding water, and the steam fluttering at the safety-valve, so as to have them all ready for starting at a moment. This is a dangerous practice, as the foregoing experiments demonstrate. While so

* London *Mining Journal*, June 28, 1856.

standing, all the atmospheric air may be expelled from the water, and it may thereby attain to a high heat, ready to generate suddenly a great steam-pressure when the feed-pump is set in motion. This is, no doubt, the cause of the explosion of many steam-boilers immediately upon starting the engine, even when the gauge indicates plenty of water. The remedy for such explosions must be evident to every engineer—keep the feed-pump going, however small may be the feed required."

On the other hand, the report of a committee appointed by the French Academy to inquire into the superheated-water theory of steam-boiler explosions indicates at least the difficulty of securing such conditions.* The committee constructed suitable apparatus, experimented in the most exhaustive manner, and investigated several explosions claimed by the advocates of the theory to have been due to this cause. They failed to superheat water under any conditions which could probably occur in practice, and the explosions investigated were shown conclusively to have resulted from simple deterioration of the boilers, or from carelessness. It is unquestionably the fact that explosions due to this cause are at least exceedingly rare, although it is not at all certain that they may not now and then take place. The ocean is constantly being traversed by thousands of steamers having surface-condensers and boilers in which the water is used over and over again, and in which every condition is seemingly favorable to such superheating of the water; but no one known instance has yet occurred of the production of this phenomenon, there or elsewhere, on a large scale, where boilers are in regular operation.

M. Donny, who first suggested the possibility of this action as a cause of boiler-explosions, has had many followers. M. Dufour,† who doubts if such explosions are possible in the ordinary working of the boiler, points out the fact, however, that boilers which are not in operation, but which are quietly cooling down after the working-hours are over, are peculiarly well

* Annales de Mines, 1886.

† Sur l'Ébullition de l'Eau, et sur une cause probable d'Explosion des Chaudières à Vapeur, p. 29.

situated for the development of this form of stored energy. He points out the known fact that many explosions have taken place under such conditions, the pressure having fallen below the working-pressure. M. Gaudry* makes the same observation. Such cases are supposed to be instances of "retarded ebullition" with decrease of pressure and superheating of the water. Many circumstances unquestionably tend to strengthen this view.

So tremendous are the effects of many explosions that M. Audrand has expressed the belief that a true explosion must be preceded by pressures approaching or exceeding 200 atmospheres;† an intensity of pressure, however, which no boiler could approximate. Mr. Hall also thinks that the shattering effect sometimes witnessed, resulting in the shattering of a boiler into small pieces, must be the effect of a sudden and enormous force, partaking of the nature of a blow;‡ and cites cases, such as are now known to be common, of an explosion taking place on starting an engine, after the boiler has been at rest and making no steam for a considerable time. M. Arago cites a number of similar instances,§ and Robinson a number in still greater detail.‖ Boilers after quietly "simmering" all night exploded at the opening of the throttle-valve or the safety-valve in the morning. The locomotive Wauregan, which exploded within sight and hearing of the Author at Providence, R. I., in February, 1856, is mentioned by Colburn as such a case. The engine had been quietly standing in the engine-house two hours, the engineer and fireman engaged cleaning and packing, preparatory to starting out. The explosion was without warning and very violent, stripping off the shell and throwing it up through the roof, and killing the engineer, who was standing beside his engine.

Mr. Robinson¶ thinks the usual cause of such explosions is

* Traité des Machines à Vapeur.

† *Comptes Rendus*, May, 1855, p. 1062.

‡ *Civil Engineers' Journal*, 1856, p. 133; *Dingler's Journal*, 1856, p. 12.

§ Annuaire, 1830.

‖ Steam-boiler Explosions, p. 62.

¶ Ibid. p. 66.

the overheating of the water, the phenomenon being in its effects very like the "water-hammer" in steam-pipes, producing shocks which the Author has shown to give rise to instantaneous pressures exceeding the working pressures ten or twenty times; the action seems, however, rather to be that "boiling with bumping" familiar to chemists handling sulphuric acid in considerable quantities. Instances have been known in which this bumping has burst pipes or severely shaken boilers and setting without producing explosion.

The deaeration of water, and the consequent superheating of the liquid, to which some explosions have been attributed, are phenomena which have been often investigated. Mr. A. Guthrie, formerly U. S. Supervising Inspector-General of Steam-vessels, states that he has made many such experiments, as follows:*

"(1) In my experiments I first procured a sample of water from the boiler of an ordinary condensing-engine; here, of course, in addition to being subjected to long-continued boiling, it had passed through the vacuum.

"(2) I procured a sample from the ordinary high-pressure non-condensing engine-boiler, which before entering the boiler had passed the heater at 210°.

"(3) I procured some clean snow and dissolved it under oil, so that there was no contact with the air.

"(4) I froze some water in a long, upright tube, using only the lower end of the ice when removed from the tube, and dissolved under oil.

"(5) I placed a bottle of water under a powerful vacuum-pump worked by steam, for two hours; agitating the water from time to time to displace any air that might possibly be confined in it, then closed it by a stop-cock, so that no air could possibly return.

"(6) I boiled water in an open boiler for several hours, and filled a bottle half-full, closed and sealed it up, so that when it became cool it would in effect be under a vacuum, agitating it as often as seemed necessary.

* *American Artisan; Locomotive*, 1880.

"(7) Another bottle was filled with the same, and sealed.

"(8) I next took some clean, solid ice, dissolved it under oil, and brought it to a boil, which was continued for an hour or more, after which it was tightly corked.

"(9) I procured a bottle of carefully-distilled water, after long boiling and having been perfectly excluded from air during the distillation.

"(10) I obtained a large number of small fish, placed them in pure, clean water in an open-headed cask, on a moderately cold night, so that very soon it became frozen over, consequently excluding the air, the fish breathing up the air in the water, so that (if I am correct in this theory) a water freed from air would be the result; but in *some* of these different processes, if not in all, I was likely to free the water from air, if it could ever possibly occur in the ordinary course of operating a steam-boiler.

"Having procured a good supply of glass-boilers adapted to my purpose, and so made that the slightest changes could be noted, and using as delicate thermometers as I could obtain, I took these samples, one after another, and brought them to the boiling-point; and every one, with no variation whatever, boiled effectually and positively at 212° Fahrenheit or under; nor was there the slightest appearance of explosion to be observed."

This evidence is, of course, purely negative.

The superheating of water, on even the small scale of the laboratory experiments of Donny, Dufour, and others, has never been successfully performed, except with the most elaborate precautions. The vessel containing the liquid must be absolutely clean; the washing of all surfaces with an alkaline solution seems to be one of the customary preliminary operations. The vessel must usually be heated in a bath of absolutely uniform temperature in order that currents may not be set up within the body of the liquid to be heated; no solid can be permitted to enter or come in contact with it; no shock can be allowed to affect it; even contact with a bubble of gas may stop the process of superheating. All these conditions are as far removed as possible from those existing in steam-boilers.

282. The Spheroidal State, or Leidenfrost's phenomenon,

as it is often called, is a condition of the water, as to temperature, precisely the opposite of that last described, its temperature being less, rather than greater, than that due the pressure; while the adjacent metal is always greatly overheated, and thus becomes a reservoir of surplus heat-energy which can be transferred at any instant to the water. This peculiar phenomenon was first noted by M. Leidenfrost about 1746. It was studied by Kläproth, Rumford, and Baudrimont,* and more thoroughly by Boutigny.

When a small mass of liquid rests upon a surface of metal kept at a temperature greatly exceeding the boiling-point of the liquid under the existing pressure, the fluid takes the form of a globule if a very small mass, or of a flattened spheroid or round-edged disk if of considerable volume, and floats around above the metal, quite out of contact with the latter, and gradually, very slowly, evaporates. The higher the temperature of the plate, the more perfect this repulsion of the liquid. Should the temperature of the metal fall, on the other hand, the globule gradually sinks into contact with it, and, at a temperature which is definite for every liquid, and is the lower as it is the more volatile, finally suddenly absorbs heat with great rapidity and evaporates often almost explosively. If contact is forcibly produced at the higher temperature of the supporting plate of metal, as under a blacksmith's hammer, a real explosion takes place, throwing drops of the liquid in every direction.

M. Boutigny found the temperature of contact to be, for water, alcohol, and ether, respectively, 142° C., 134°, and 61° (287° F., 273°, and 142°). In all cases the temperature of the liquid was independent of that of the metal, and somewhat below the boiling-point. It is found, also, that a real and powerful repulsion is produced between metal and liquid; this is supposed to be due, in part at least, to the cushion of vapor there interposing itself. Contact is accelerated by the introduction of soluble salts into the liquid.

It is supposed by many writers that this phenomenon may play its part in the production of explosions of steam-boilers,

* Ann. de Chemie et de Physique, 2d series, t. lxi.

and especially in cases in which there seems some evidence that, immediately before the explosion, there was no apparent overheating of the parts exposed to the action of the fire, and in those still more remarkable instances in which the shattered parts had been, to all appearance, much stronger than other portions which had not been ruptured; no evidence existing of low-water or overheating at the furnace, and the pressure being, the instant before the accident, at or below its usual working figure. Bourne* has no doubt that this does sometimes take place. Colburn gives a number of instances of explosions taking place under, apparently, precisely such conditions; and Robinson† also cites several, in some of which the plates of the shell were badly shattered, as by a concussive force. In some such instances evidences of overheating, but only far below the water-level, known to have existed immediately before the explosion, have been observed, indicating repulsion to have there occurred. This latter is simply still another instance of bringing about the same results as when pumping water into an overheated boiler in which the water is low.

Mr. Robinson‡ tells of a case in which a nearly new locomotive, standing in the house, with a pressure, as shown but a moment before by the steam-gauge, of but 40 pounds,—one third its presumed safe working pressure,—the fire low and everything perfectly quiet, exploded with terrible violence, shattering the top of the boiler directly over the firebox into many parts. That such explosions might occur were the metal actually overheated under water, is shown by experiences not at all uncommon.

In the work of determining the temperatures of casting alloys tested by the Author § for the United States Board appointed in 1875 to test iron, steel, and other metals, at the first casting of a bar composed of 94.10 copper, 5.43 tin, while pouring the metal into the water for the test, an explosion took place which broke the wooden vessel which held the water, and threw

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* Treatise on the Steam-engine. 1868.

† Steam-boiler Explosions, p. 33.

‡ Steam-boiler Explosions, p. 62.

§ Report on Copper-tin Alloys. Washington, 1879.

water and metal about with great violence. It appears probable that the metal was heated to an unusually high temperature, as in pouring other metals when at a dazzling white heat explosions sometimes took place, but they were usually not violent enough to do more than make a slight report as the hot metal touched the water. Another bar was cast at an extremely high temperature, being at a dazzling white heat. On pouring a small portion into water in attempting to obtain the temperature, a severe explosion took place, and this was repeated every time that even a small drop of the molten metal touched the water. The cold ingot-mould was then filled with this very hot metal. After the metal remaining in the crucible had stood for several minutes and had cooled considerably, it could be poured into water without causing the slightest explosion. Thus it would seem that the temperature at which contact with the water is produced may have an important effect upon the violence with which the steam is generated, and that of the explosion so produced. The explosions sometimes taking place with fatal effect in foundries when molten metal is poured into damp or wet moulds are produced in the manner above illustrated. They are usually apparently of the "fulminating class." Another instance occurred within the cognizance of the Author, even more striking than either of the above.*

Two workmen in a gold and silver refinery were engaged in "graining" metal, which process consists in pouring a small stream of melted metal into a barrel of water, while a stream of water is also run into the barrel to agitate the water already there. Suddenly an explosion occurred which literally shivered the barrel, and threw the workmen across the room. Every hoop of the barrel, stout hickory hoops, was broken. The staves, seven eighths of an inch thick, and of oak, were not only splintered, but broken across; and the bottom, which was resting on a flat surface, and which was of solid oak an inch in thickness, was split and broken across the grain. A box on which stood the man who was pouring the metal was converted into kindling wood. The metal, though scattered somewhat, for the

* Reported in the Providence (R. I.) *Journal*, Feb. 2, 1881.

most part remained in place, but the water was thrown in all directions.

This explosion of an open barrel, like the preceding cases, was evidently due to the deferred thermal reaction of the water with a mass of very highly heated metal, with which it was finally permitted to come in contact at a temperature which allowed an explosive formation of steam. This class of explosions, by which open vessels are shattered and the water contained in them *atomized*, are by many engineers believed to exemplify the terrible *explosions fulminantes* of French writers on this subject.

The temperature of maximum vaporization, with iron plates, was reported by the committee of the Franklin Institute to be 346½° F. (175° C.) and that of repulsion 385° F. (196° C.), and to be the same under all pressures. Any cause which may retard the passage of heat from the iron to the water, though but the thinnest film of sediment, grease, or scale, may permit such increase of temperature as may lead to repulsion of the water, the overheating of the metal, the production of the spheroidal condition, and the accidents due to that phenomenon, *provided* that the fire be so driven as to supply more heat than can be disposed of in ordinary working by the circulation and vaporization then going on. Robinson's experiments with safety-plugs indicate that a good circulation is usually a sufficient insurance against this action; and experience with the boilers of locomotives and of torpedo-boats, in which from 50 to 100 pounds of coal per square foot (244 to 488 kilogs. on the square metre) of grate are burned every hour, shows that the risk, with steam-boilers of good design, is not great. With impure water and defective circulation Robinson observed many instances of singular and dangerous phases of this action.* It is suggested that many explosions of locomotives on the road or at stations may be due to the impact, on the shells of their boilers, of water thus projected from overheated iron below the water-line. In many such cases the engines have not left the rails, the break taking place just back of the smoke-box or near the fire-

* See his Steam boiler Explosions, pp. 40–46.

box, and from the impact of water thus thrown from the tube-sheets.

M. Melsen* experimentally proved it possible to prevent the occurrence of the spheroidal condition by the distribution of spurs or points of iron over the endangered sheets.

The conductivity of the metal has an important influence on the effect of contact, suddenly produced, between the red-hot solid and the liquid. Professor Walter R. Johnson observed, in his elaborate experiments,† that brass produced much greater agitation of the water when submerged at the red heat than did iron. He also noted the singular fact that water at the boiling-point, thrown upon red-hot iron, requires more time for evaporation than cold water, probably in consequence of the greater efficacy of the latter in bringing down the temperature of the metal to that of maximum rapidity of action. The contact with the iron of incrustation, oxide, or other foreign matter accelerated this process also. Johnson found that beyond the temperature of maximum repulsion vaporization was accelerated by further elevation of temperature.

At the meeting of the British Association in 1872, Mr. Barrett read a paper upon the conditions affecting the spheroidal state of liquids and their possible relationship to steam-boiler explosions. The presence of alkalies or soaps in water perceptibly aids in the production of the spheroidal state. A copper ball immersed in pure water produced a loud hissing sound and gave off a copious discharge of steam. On adding a little soap to the water the ball entered the liquid quietly. Albumen, glycerine, and organic substances generally produced the same result. The best method is to use a soap solution, and to plunge into this a white-hot copper ball of about two pounds weight. The ball enters the liquid quietly, and glows white hot at a depth of a foot or more beneath the surface. Even against such pressure the ball will be surrounded with a shell of vapor of an inch in thickness. The reflection of the light from the bounding surfaces of the vapor-bubble surrounding the glowing

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* Bull. de l'Académie Royale de Belgium, April, 1871.

† Reports on Steam-boilers, H. R., 1832, p. 111.

ball gives to the envelope the appearance of burnished silver. As the ball gradually cools, the bounding envelope becomes thinner, and finally collapses with a loud report and the evolution of large volumes of steam. Mr. Barrett makes the suggestion that the traces of oil, or other organic matters which find their way into a steam-boiler, may similarly produce a sudden generation of steam sufficient to account for certain problematical explosions, and thus lends some strong confirmatory evidence to the idea often promulgated by others within and without the engineering profession.

283. **Steady Rise in Pressure** has been shown by the experiments of the committee of the Franklin Institute, and by numerous cases of explosion, both before and since their time, to be capable of producing very violent explosions. In such cases, the steam being formed more rapidly than it is given exit, the pressure steadily increases until a limit is found in the final rupture of the weakest part of the boiler. Should this break occur below the water-line, and be the result of long decay or injury, no explosion may ensue; but should the rupture be extensive, or should it occur above or near the surface of the water, the succession of phenomena described by Clarke and Colburn may follow, and an explosion of greater or less violence may take place. The intensity of the effect will depend largely upon the quantity of stored energy liberated, and partly upon the suddenness with which it is set free. A slowly-ripping seam or gradually extending crack would permit a far less serious effect than the general shattering of the shell, or an instantaneously produced and extensive rent.

The time required to produce a dangerous pressure is easily calculated when the weight of water present, W, the range of temperature above the working pressure and temperature, $t_1 - t_2$, and the quantity of heat, Q, supplied from the furnace are known, and is

$$T = \frac{W(t_1^\circ - t_2^\circ)}{Q}.$$

Professor Trowbridge gives the following as fair illustrations of such cases:*

* Heat as a Source of Power, p. 191.

(1) A marine tubular boiler is of the largest size, such that

$$W = 79{,}000 \text{ lbs. of water.}$$

Suppose the working pressure to be $2\frac{1}{2}$ and the dangerous pressure 4 atmospheres.

The boiler contains 5000 square feet of heating-surface; and supposing the evaporation to be 3 lbs. of water per hour for each square foot, we shall have, taking 1000 units of heat as the thermal equivalent of the evaporation of 1 lb. of water,

$$t_1 - t = 29^\circ \text{ F.}$$

$$Q = \frac{5000 \times 3 \times 1000}{60};$$

$$T = \frac{79{,}000 \times 29}{\frac{5000 \times 3 \times 1000}{60}} = 9.1 \text{ minutes.}$$

(2) A locomotive boiler, containing 5000 lbs. of water, having 11 square feet of grate-surface, and burning 60 lbs. of coal per hour on each square foot of grate, each pound of coal evaporates about 7 lbs. of water per hour, making 77 lbs. of water evaporated per minute.

Suppose the working pressure to be 90 lbs., and the dangerous pressure to be 175,

$$t_1 - t = 50^\circ \text{ F.}$$

$$T = \frac{5000 \times 50}{77 \times 1000} = 3\tfrac{1}{2} \text{ minutes.}$$

(3) *The Steam Fire-engine.*—The boiler contains 338 lbs. of water and 157 square feet of heating-surface. Supposing each square foot of heating-surface to generate but 1 lb. of steam in one hour, the pressure will rise from 100 to 200 lbs. in

$$T = 7 \text{ minutes.}$$

(4) To find, in the same boiler, how long a time will be required to *get up steam;* that is, to carry the pressure to 100 lbs.

If we suppose but $1\frac{1}{2}$ cubic feet of water in the boiler, we shall have

$$T = \frac{93 \times 117}{\frac{157 \times 1000}{60}} = 4.1 \text{ minutes.}$$

Thus, if W is diminished, the time T is diminished in the same proportion. The lowering of the water-level from failure of the feed-apparatus increases the danger, not only by exposing plates to overheating, but by causing a more rapid rise of pressure for a given rate of combustion.

Gradual increase of pressure can never take place if the safety-valve is in good order, and if it have sufficient area.

The sticking of the safety-valve, either of its stem or its seat, the bending of the stem or the jamming of the valve by a superincumbent object or lateral strains, and similar accidents, have produced, where boilers were strong and otherwise in good order, some of the most terrific explosions of which we have record. The parts of the boiler have been thrown enormous distances, and surrounding buildings and other objects levelled to the ground, while the report has been heard miles away from the scene of the disaster.

The records of the Hartford company up to 1887 include accounts of 26 explosions of vessels detached from the generating boiler, used at moderate pressures for various purposes in the arts, and there have been many others of less importance that were not considered worthy of public mention. It is concluded that the percentage of explosions among bleaching, digesting, rendering, and other similar apparatus is ten times greater than among steam-boilers at like average pressures, and the destructive work done is quite as astonishing as that by the explosion of ordinary steam-generators.*

This is sufficiently decisive of the question whether it is possible to produce destructive explosions of boilers simply by excess of pressure above that which the vessel is strong enough to withstand. In these cases low-water and all the other special causes operating where fire and high temperatures exist,

* *The Locomotive*, 1887.

and such absurd theories as the generation of gas or the action of electricity, are eliminated; and it is seen that mere deterioration and loss of strength, or a rise of steam-pressure, even where there is an ample supply of water, may produce explosions of the utmost violence.

284. **The Relative Safety of Boilers** of the various types is determined mainly by their general design, and their greater or less liability to serious and extensive injury by the various accidents and methods of deterioration to which all are to a greater or less extent liable. The two essential principles by which to compare and to judge the safety of boilers are:

(1) Steam-boilers should be so designed, constructed, operated, inspected, and preserved as not to be liable to explosion.

(2) Boilers should be so designed and constructed that, if explosive rupture occurs at all, it shall be with a minimum of danger to attendants and surrounding objects.

The prevention of liability to explosion, and the provision against danger should explosion actually take place, are the two directions in which to look for safety.

As Fairbairn has remarked, the danger does not consist in the intensity of the pressure, but in the character and construction of the boiler.* Other things being equal, the boiler, or that form of boiler in which the original surplus strength of form and of details is greatest, and which is at the same time best preserved, is the safest. That class in which original strength is most certainly and easily preserved has an important advantage; those boilers in which facilities for constant oversight, inspection, and repairs are best given are superior in a very important respect to others deficient in those points. For example, the cylindrical tubular boiler, if properly set, is very accessible in all parts, and may be at all times examined: it offers peculiar facilities for inspection and the hammer-test, and can be readily kept in repair; but it is liable, in case of its becoming weakened by corrosion over any considerable area or along any extended line of lap, to complete disruptive explosion.

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* Engineering Facts and Figures, 1865.

On the other hand, the various "sectional," or so-called "safety," boilers are rarely as convenient of access or of inspection, and cannot usually be as readily and completely cleaned; but they are so designed and constructed as to be little, if at all, liable to dangerous explosive rupture, and if a tube or other part bursts it is not likely to endanger life or property. That boiler is, therefore, on the whole, best which is least liable to those kinds of injury which lead to explosion, and which is least likely to do serious harm should explosion actually take place.* Those who select the tubular boiler are commonly influenced mainly by considerations of cost and the first of the above considerations; while the users of the water-tube sectional boiler are controlled by the second, in so far as either considers this form of risk at all.

During the experiments of Jacob Perkins, about 1825 and later, the value of the "sectional" boilers, where high-pressures are adopted, was well shown. He frequently raised his steam-pressure to 100 atmospheres,† and in his earlier work rupture often took place, but no ill effects followed. The division of the boiler into numerous compartments saved the attendants from injury. In a letter to Dr. T. P. Jones, dated March 8, 1827,‡ Mr. Perkins states that he had worked at the above-mentioned pressure with a ratio of expansion of 12; his usual pressure was about two thirds that amount, and the ratio of expansion 8. Mr. Perkins was then building an engine to safely carry a pressure of 2000 pounds per square inch.§

285. Defective Designs, causing explosion, are not as common as many other causes. They exist, however, more frequently than is probably usually supposed. The defects are generally to be observed in the staying of such boilers as require bracing; in the insertion of the heads of plain cylindrical boilers; in the attachment of drums, and the arrangement of

* Dr. E. Alban, following John Stevens, was probably the first to enunciate the principle, "so construct the boiler that its explosion may not be dangerous." The High-pressure Steam-engine, 1847, p. 70.

† Jour. Franklin Inst., vol. iii., p. 415.

‡ Ibid., p. 412.

§ Reports on Steam-boilers, H. R., 1832, p. 188.

man-holes and hand-holes; and, less frequently, in the selection of the proper thickness and quality of iron for shells and flues. Such defects as these are the most serious possible; they are not only serious in themselves and at the start, but are of a kind which is commonly very certain to be exaggerated, and rendered continually more dangerous with age. A thin shell grows constantly thinner, a weak stay or brace weaker, and an unstayed head more likely to yield every day; while a flue originally too thin is all the time overstrained, not simply by the steam-pressure, but also by the action of the relatively stronger parts around it. The most minute study of every detail and the most careful calculation of the strength of every part, with an allowance of an ample factor of safety, are the essentials to safety in design.

Faulty design in bracing is illustrated by an explosion which took place in New York City, January 15, 1881, by which, fortunately, however, no loss of life was caused. A dome-head, proportioned and braced as shown in the next figure, was blown out and tore up a sidewalk, under which the boiler was set,

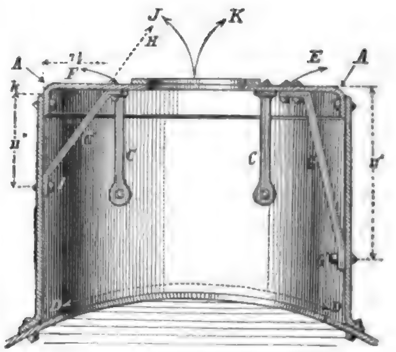


FIG. 133.—DOME AND HEAD.

doing no other damage. The case was examined by Mr. Rose, who reported substantially as follows:

The dome-crown tearing around the edge at A, also tore across at B, being thus completely severed. The iron at the fractures was of excellent quality. The plate showed lamination in places, and the crack around A was rusty, and evidently

not of recent formation. The six stays, three of which are shown in place at *C*, Fig. 133, were all in position in the dome, and their surfaces of contact with the dome were covered by a black polish, indicating movement and abrasion.

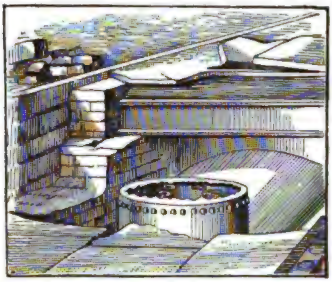


FIG. 134.—EXPLOSION OF DOME.

Apparently, as the pressure and temperature increased and decreased the dome-head might lift and fall, bending on *A* as a centre; thus, taking *I* as a centre, the movement of *C* would

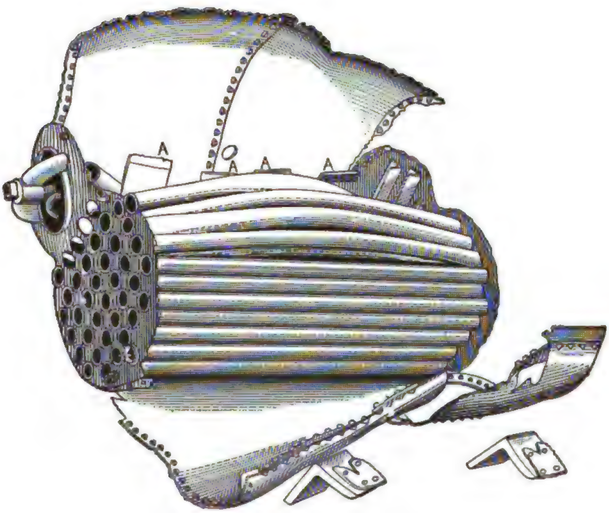


FIG. 135.—DEFECTIVE FORM.

be in the direction of *F*, while at *D* the direction would be toward *J*, and the direction of motion of the two would nearly

coincide. The exploded dome shows an indentation at *I*, due to the motion of the foot of the stay.

Another error in the design of this boiler is that the diameter of the dome-shell is 34 inches, and a circle of iron about 18 inches in diameter is punched out of the shell at *D*. This opening is required only to admit an inspector or workman to the interior of the boiler; hence it is several inches wider than it should be.

Defective design is illustrated in the case of the next boiler, the explosion of which left it in the form shown in Fig. 135.*

This boiler consisted of two incompletely cylindrical shells, united as in the next figure, and ineffectively stayed at the lines of contact. This is a form which, insufficiently braced, becomes peculiarly dangerous. In the case illustrated, the braces yielded, after having been weakened by continual alteration of form, and split the two shells apart as seen. It is probably possible to brace boilers of this type safely, but it is better to avoid their use. They have sometimes been used for marine purposes, where lack of space compelled special expedients, the bracing consisting of strong bolts with nuts and washers on the outside of the shell—a comparatively strong and safe construction.

FIG. 136.—JUNCTION OF SHELLS.

Steam-domes are a source of some danger and of additional expense, however well designed and attached; and it is probably good economy, all things considered, to dispense with them altogether, using a dry pipe instead, and expending the amount of their extra cost on an increase in size of boiler over that which would have otherwise been selected. The large boiler will steam easier and more regularly, will give drier steam, and will be less liable to danger of deterioration or of explosion. A steam-drum above the boiler and connected by two separate nozzles, or a drum connecting the several boilers of a battery, is not subject to the objections which apply to the attached dome.

286. Defective Construction, material, and workmanship are responsible for many explosions of steam-boilers. Thin,

* *Locomotive*, Feb. 1880.

laminated, or blistered sheets, imperfect welds in bracing, the strain produced by the drift-pin, carelessness in the attachment of nozzles and drums, and in neglect of the precaution of strengthening man-holes and hand-holes, and bad riveting, are all common causes of weakness and accidents. Only the most careful and skilful, as well as conscientious, builders can be relied upon to avoid all such faults, and to turn out boilers as strong and safe as the designs may permit.

In all cases, careful and unintermitted inspection by an experienced, competent, and trustworthy inspector should be provided for by the proposing purchaser and user of the boiler. In the case of some of the more modern forms of boiler, constructed under a system of manufacture which includes some machine fitting and working to gauge of interchangeable parts, with regular inspection before assemblage, this supervision becomes less essential, and a careful test and trial, previous to acceptance, may be all that is necessary to insure a satisfactory and safe construction. Wherever defective material or bad workmanship is detected, the fault should always be corrected before the boiler is accepted, and previous to any trial or use under steam. Careless riveting and the use of the drift-pin are defects which cannot often be readily detected afterward, and they are such common causes of explosion that too much care cannot be taken to avoid any establishment of which the reputation in this regard is not the best.

FIG. 137.—DEFECTIVE WELDING.

Defective welds, the cause of many unfortunate accidents following the yielding stays or braces, are among the most

common and least easily detected of all faults. They are due to the difficulty of producing metallic contact in abutting surfaces between which particles of scale and superficial oxidation may interpose. The grain of the iron, as illustrated in the accompanying engraving, is broken at such junctions, and it is difficult to secure a good weld, and next to impossible to determine until it actually breaks whether it is seriously unsound.

Defective workmanship is often exhibited most strikingly by the distorted forms of rivets, revealed after explosion has caused a fracture along the seam, or when the yielding of the weakened seam has resulted in an explosion. The following illustrations of a variety of cases of such distortion, all taken from a single boiler,* show how very serious this kind of defect may be. It is not to be presumed that such carelessness or worse, as is here exemplified, is to be attributed to the builder himself, but rather to the fault of workmen carefully concealing their action from the eye of the foreman or inspector. No law or rule can protect the purchaser from this kind of fault; his only reliance must be upon the reputation of the maker and his workmen, and the vigilance and skill of his inspector.

FIG. 138.—Rivet "driven" in overset holes, the conical point broken off by the tearing apart of the plates, the head

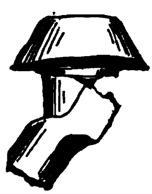


FIG. 138.

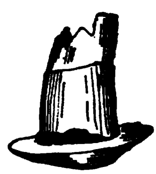


FIG. 139.

nearly severed from the body, and probably weakened in "driving."

FIG. 139.—Rivet "driven" in overset holes, head broken off by the tearing apart of the plates, conical point also nearly

* *Locomotive*, Feb. 1880.

broken off, bad sample of "driving," cone too flat to properly hold down the plate.

The next figure illustrates a group of similar distorted rivets which played their part in the production of an explosion.

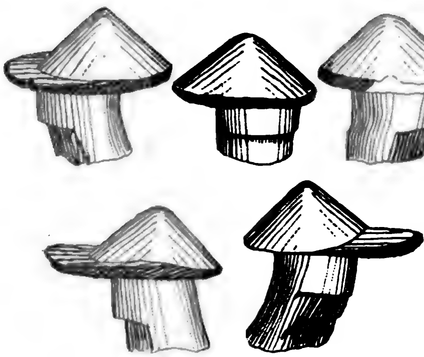


FIG. 140.—DEFECTIVE RIVETS.

FIG. 141.—Rivet "driven" in slightly overset holes, point excentric and not symmetrical, too flat to properly secure the edge of the plate.

FIG. 142.—Rivet "driven" in badly overset holes, very weak.

FIG. 141.

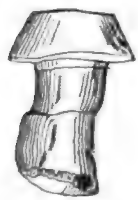


FIG. 142.

See Figs. 143, 144, 145, which were "sheared" at the time of the explosion. The dark shading on lower end, Fig. 142, indicates an old crack.

FIGS. 143, 144, 145.—Samples selected from a number taken from a "sheared" seam, which was believed to be the initial break from which the explosion arose. They were no doubt similar to Fig. 142 before they gave way.

The Author, on one occasion, picked out with his fingers

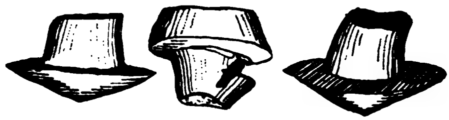


FIG. 143. FIG. 144. FIG. 145.

twelve consecutive rivets, deformed like those here illustrated, from a torn seam in an exploded boiler.

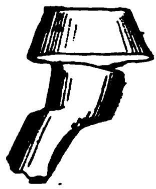


FIG. 146.

FIG. 146.—Rivet "driven" in overset holes; it was probably fractured under the head in driving. Taken from a seam that was broken through the rivet-holes.

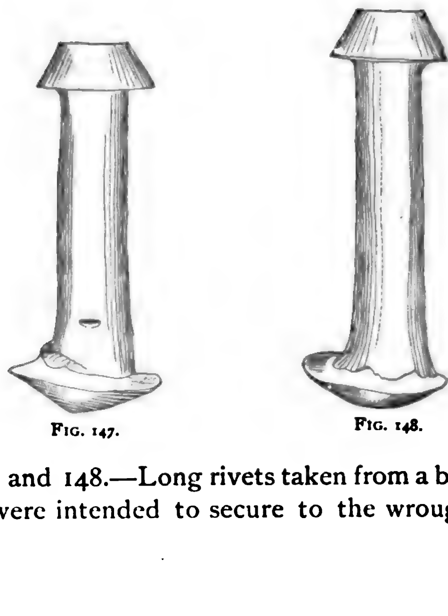


FIG. 147. FIG. 148.

FIGS. 147 and 148.—Long rivets taken from a broken casting which they were intended to secure to the wrought-iron head

of the boiler. The holes in the wrought-iron plate were "drifted" and chipped to allow the rivets to enter, as shown by the enlarged portion of the body. This irregular upsetting and the sharp little wave of iron on the body of Fig. 147 indicate the thickness of the wrought-iron plate.

287. Developed Weakness, usually a consequence of progressing decay by corrosion, is the most common of all causes of the explosion of steam-boilers. A boiler, designed and constructed of the best possible proportions and of the best of materials, having at the start a real factor of safety of six, may be assumed to be as safe against this kind of accident as possible; but with the beginning of its life decay also begins, and the original margin of safety is continually lessened by a never-ceasing decay. The result is an early reduction of this margin to that represented by the difference between the working pressure and that fixed as a maximum by the inspector's tests. Should this difference be sufficient to insure against accident resulting from further depreciation in the interval between inspector's or other tests, explosion will not occur; should this margin not be sufficient, danger is always to be apprehended, and almost a certainty that rupture, and possibly explosive rupture, will at some time occur. This margin is, legally, usually fifty per cent; it is too small to permit the proprietor to feel a real security. It is usually thought that the tests should show soundness under pressures at least double the regular working pressure at which the safety-valve is set.* Many cases have been known in which the boiler has yielded at the working pressure not very long after the regular official inspection and pressure-test had taken place.

Such an example was that of the explosion of the boiler of the Westfield, in New York Harbor, in June, 1871.

The steam ferry-boat Westfield is one of three boats which have formed one of the regular lines between New York and Staten Island. The Westfield made her noon trip up from

* Experiments made by the Author, and later by other investigators, have indicated the possibility that an apparent factor of safety of *two*, under load momentarily sustained, may not actually mean a factor exceeding one for permanent loading.—"Materials of Engineering," vol. i., § 133; vol. ii., § 295.

the island to the city on Sunday, July 30th, and while lying in the New York slip her boiler exploded, causing the death of about one hundred persons and the wounding of as many more.

The boiler is of a very usual form, as represented in Fig. 149, and is known as a "marine return-flue boiler."

The diameter of its shell—the cylindrical part was ruptured—is ten feet; its thickness, No. 2 iron, twenty-eight hundredths inch.

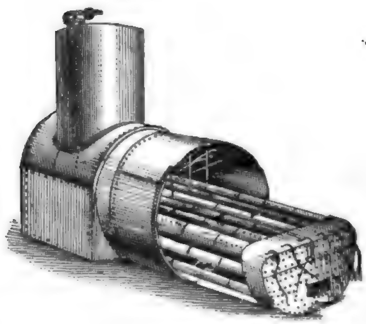


Fig. 149.—Boiler of the Westfield.

The evidence indicated that the explosion occurred in consequence of the existence of lines of channelling and long-existing cracks, by which the boiler was gradually so weakened that, six weeks after its inspection and test, the pressure of steam being allowed by the engineer to rise slightly above the pressure allowed, the boiler was ruptured, giving way along a horizontal seam and tearing a course out of the boiler.

The common lap-joint customarily adopted in the construction of boilers is liable to such serious distortion under very heavy pressures as to produce leakage before actually yielding, and this leakage is sometimes so great as to act as a safety-valve. Thus, suppose a straight strip of plate riveted up in parts as in Fig. 150.* A heavy pull will cause distortion as shown, in all cases except where a butt-joint is made with a covering strip on each side. If the metal is brittle and the rivet-heads strong, preventing the bending of the plate on the

* See *Locomotive*, Oct. 1880.

line of rivet-holes, the plate will probably break adjacent to *G* or *F*, Fig. 150; or in the middle, *I* and *H*. But should the plates be ductile or the rivet-heads weak, the break would occur at the line through the holes.

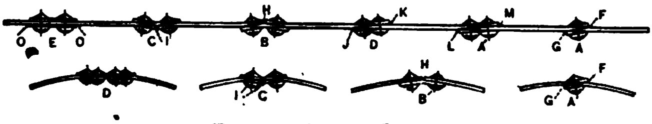


FIG. 150.—YIELDING JOINTS.

If the plates, Fig. 150, *A*, etc., were straight at the joint, the extreme end, *L*, must contract and the outer one expand at *M*, involving in the one a compression or upsetting, and in the other drawing the metal. If the joint be a butt, with a single outer cover, *C*, a similar contraction must take place at both ends, and a contraction of the middle of the covering strip, while the opposite would take place in the case of the joint with the inner cover, *B*. These distortions are not likely to take place in a *transverse* seam of a cylindrical boiler-shell from internal pressure. The butt-joint, with two covering plates, *E*, would retain its shape.

Lapped longitudinal joints are shown at *A'*. Single-riveted and single-covered butts at *B'* and *C'*. *D'* shows a double-riveted, single-covered butt. The next figures (151, 152) show

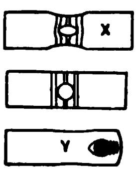
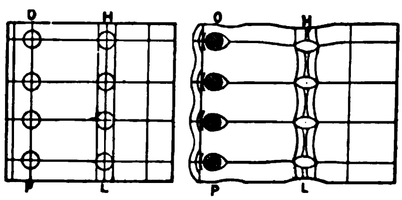


FIG. 151.



Before Stretching. After Stretching.

FIG. 152.

the effect of strain on rivet-holes and on holes filled by the rivet.

Multiple explosions are not infrequent. They usually occur in consequence of the explosion of one of a battery, with the result of injuring adjacent boilers in such manner that they also

explode, the phenomena following each other so quickly as to produce the appearance of simultaneous explosion. It is possible also that in some cases an accession of pressure in a set of boilers may take place with such suddenness as to explode several, notwithstanding there may exist a difference in their resisting power, the weakest not being given time to act as a safety-valve to the rest. It is doubtful, however, whether such cases can often if ever arise.

288. General and Local Decay introduce vastly different degrees and elements of danger. As has been elsewhere stated, in effect, an explosion comes of extended rupture; while local injuries or breaks, if they do not lead to wider injury, cannot cause widespread disaster. Hence, general corrosion, extending over considerable areas of plate or along lines of considerable length, is a cause of danger of complete disruption and explosion. A corroded spot in a firebox, a loosened rivet, or even a broken stay, if the boiler be otherwise well proportioned, well built, and in good order, may not be a serious matter; but a thinned sheet in the shell, a long groove under a lap, a line of loose rivets, or a cluster of weakened stays or braces, will certainly be most dangerous. General or widespread corrosion is very liable to lead to explosion; local and well-guarded corrosion may cut quite through the metal, and simply cause a leak or an unimportant "burst." Old fireboxes are often seen covered with "patches" in places, and yet they very rarely explode. Such a state of affairs may, nevertheless, by finally producing large areas of patched and fairly uniformly weak portions of the boiler, lead to precisely the conditions most favorable to explosion. A steam-boiler experimentally exploded at Sandy Hook, N. J., September, 1871,* had previously, by repeated rupture by hydraulic pressure and patching, been gradually brought into precisely this state, and exploded under steam at 53½ pounds,—about four atmospheres pressure,—a slightly lower pressure than it had sustained (59 pounds) at its last test. On this occasion, when a pressure was reached of 50 pounds per square inch, a report was heard which was prob-

* Journal Franklin Institute, January, 1872.

ably caused by the breaking of one or more braces, and at 53½ pounds the boiler was seen to explode with terrible force. The whole of the enclosure was obscured by the vast masses of steam liberated; the air was dotted with the flying fragments, the largest of which—the steam-drum—rising first to a height variously estimated at from 200 to 400 feet, fell at a distance of about 450 feet from its original position. The sound of the explosion resembled the report of a heavy cannon. The boiler was torn into many pieces, and comparatively few fell back upon their original position.

FIG. 153.—CORROSION.

Thus corrosion may affect a single spot in a boiler, in which case a "patch," if properly applied, should make the boiler nearly as strong as when whole. A series of weak spots near each other may so weaken a boiler as to produce explosion, as may any considerable area of thin plate, although, when occurring in the stayed surfaces of a firebox, the metal may become astonishingly thin. A sketch of spots of corrosion is shown in Fig. 153, which represents the cause of an actual explosion. This cause of explosion may be either internal or external, and is induced internally by bad feed-water, and externally by dampness or by water leaking from the boiler, either unseen or neglected. It is always dangerous to have any portion of a boiler concealed from frequent observation.

The effect of covering a part of a sheet subject to corrosion by solid iron, as by the lap of a seam, is shown in the next figure, which also exhibits a common method of corrosion along a seam. The same effect is seen still more plainly in the suc-

ceeding figure, in which the pitting which so often attends the use of the surface-condenser is also well shown.

289. **The Methods of Decay** are as various as the forms and location of the parts subject to corrosion. As Colburn* has said: "As a malady, corrosion corresponds, in its comparative frequency and fatality, to that great destroyer of human life, consumption;" and it has as innumerable phases and periods of action. The two most common methods of decay are the general, and here and there localized, corrosion that goes on in all boilers, and in fact on all iron exposed to air and carbonic acid, in presence of moisture; and the concentrated and localized oxi-

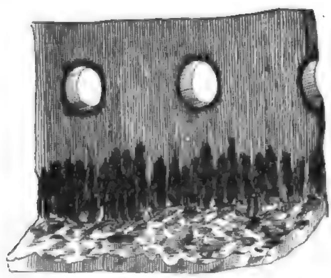


Fig. 154.—Corrosion at a Seam.

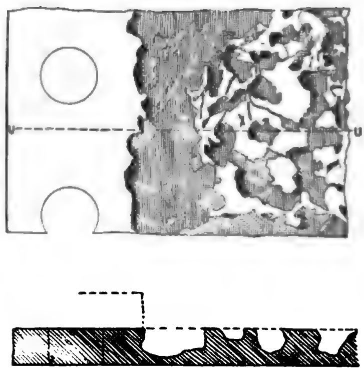


Fig. 155.—"Pitting."

dation that is often seen along the line of a seam at the edge of the lap, where the continual changing of form of the boiler is as constantly producing an alternate flexing and reflex motion of the sheet, which throws off the oxide as fast as formed along that line, and exposes fresh, clean metal to the corroding influence. A groove or furrow is thus in time produced, which may, as occurred in the case of the Westfield (Fig. 149), actually cut through the sheet before explosion takes place.

The phenomenon known as "grooving" or "furrowing" is well illustrated by the case just mentioned, in which this action was originally started, probably, by the carelessness of the workman, who, either in chipping the edge of the lap along a girth-

* Trans. Brit. Assoc. 1884.

seam, or in calking the seam, scored the under-sheet along the edge of the lap with the corner of his chisel or with the calking-tool. This is a very common cause of such a defect.

The boiler was broken into three parts. The first, and by far the largest part, consisted of the furnaces, steam-chimney and flues, with a single course of the shell; the second consisted of two courses of the outside of the shell next the back-head, together with that head, to which they remained attached; the third piece consisted of a single complete course from the middle of the cylindrical shell, which was separated at one of its longitudinal seams, partially straightened out and flung against the bottom and side of the boat. This last piece remained opposite its original position in the boiler before the explosion, while the first and second pieces went in opposite directions, the former finally lying several feet nearer the engine than when *in situ*, and against the timbers of the "gallows-frame," while the latter piece was thrown fifty feet forward into the bow of the boat, where it fell, torn and distorted. The longitudinal seam, along which piece number three separated, and the deep score or "channel" cutting nearly through in many places, and presenting every evidence of being an old flaw, were plainly seen. The mark made by a chisel in chipping, and that of the calking-tool, were seen, and indicated the probable initiative cause of the flaw.

The Author examined this piece and found an old crack or "channel" cut along the edge of the horizontal lap referred to as being at the ends of the sheet, and in some places so nearly through that it was difficult to detect the mere scale of good iron left, while in other places there remained a sixteenth of an inch of sound metal. Fig. 156 exhibits a section of the crack.

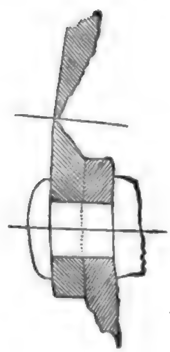


FIG. 156.

Were this the weakest place in the boiler, and the *least thickness* here one sixteenth of an inch, the tensile strength being equal to the average determined by the tests made of the iron, the pressure required to rupture such a boiler, ten feet in diameter,

would be $44079 \times \frac{1}{16} \times 2 \div 120 = 47$ pounds per square inch, nearly. A pressure of 27 or 28 pounds would burst it open where the least thickness was slightly more than one thirty-second of an inch. One portion may be supported, to some extent, by a neighboring stronger part. Along this longitudinal seam the limit of strength would seem to have been about 30 pounds per square inch, which is about the pressure at which the boiler exploded, this seam ripping for a distance of several feet. The original strength of the boiler was equal to about 120 pounds along the horizontal seams,—its then weakest parts,—provided that the iron had, when new, the average strength of the specimens which we have tested. In the vertical seams may be seen, in some places, similarly weakened portions, the cracks running usually from rivet to rivet, and here and there exhibiting marks that show the wedging action of the "drift-pin," and many places, both in longitudinal and girth-seams, are cut by the chisel and marked by the "calking-tool."

These lines of "furrowing" are sometimes continuous, and sometimes interrupted by portions of good iron. They are probably in most cases caused by changes in form of the boiler with variations of temperature and pressure, some line of local weakness determining the line along which the plate shall bend, and this bending taking place continually, though ever so slightly, along the same line precisely, finally produces rupture. This change of form of the shell of a boiler may be due to either the constantly occurring variation of pressures, as steam is made or is blown off during working hours; or it may be produced by changes of temperature. Large and thin boilers are especially liable to this form of injury. Bad methods of support may permit or may cause variations of form and this defect, which is all the more dangerous that it is difficult in many cases to detect it. Water trickling from leaks sometimes causes a kind of grooving along its path, hardly less serious in its nature and extent.

Sometimes this action produces a narrow crack, and at other times, as above stated, as the rust formed is thrown or scoured off the iron at the bend, leaving a comparatively clean surface

oxidation is probably accelerated, and the fault takes the form of a groove or furrow. If unperceived, this goes on until a rupture or an explosion occurs.

Of forty explosions of locomotive boilers noted in British Board of Trade reports,* eighteen gave way at the firebox and twenty at the barrel. Of these twenty, every one was the result of "grooving" or cracks along the lap of seams, all of which were lap-joints. The grooves were most common; they always occurred along the edge of the inside overlap, just where the changes of form with varying pressure would concentrate their effects. Such results are sometimes also seen at butt-joints, especially where a strip has been used inside. The racking action of the engines may produce precisely the same effect. Wherever change of form is felt, grooving or furrowing and cracking may be expected to be found in time. Where the boiler is already heavily strained along one of these lines of reduced thickness, any slight added stress, as a jar, or the action of a calking-tool, as when leaks in boilers under pressure are being calked, may precipitate an explosion, the break following the groove or crack just as a stretched drum-head may yield to the scratch of a knife.

290. Differences in Temperature between parts of a boiler more or less closely connected in the structure may produce serious strains, and some instances of explosion have been attributed to this cause.

Changes of temperature occur as steam is raised or blown off from a boiler, and its temperature becomes at one time that due the steam-pressure, and then it falls to that of the atmosphere each time steam is blown off. It will change its form more or less, and will usually be subjected to some strain by this process. Again, while actually at work, the steam-space and upper portion of the water-space are at the temperature of steam at the working pressure, while the lower part is continually varying in temperature from that of the feed-water to the maximum which it attains after entrance. This difference of temperature

* "Wear and Tear of Steam-boilers." F. A. Paget, Trans. Soc. of Arts, 1865; London, 1865, p. 8.

between the upper and lower parts of the boiler, as well as between other portions, causes a continual tendency to distortion; and if this distortion be resisted, a stress is thrown upon the parts equal to that which would be required, acting externally, to remove the distortion, if produced. The stress is also equal to the mechanical force that would be necessary to produce similar distortion.

Thus, had the temperature of the main and upper part of the Westfield's boiler been, after the entrance of the feed-water, 273°, or that due to about twenty-seven or twenty-eight pounds steam, while the feed-water had a temperature of 73°, the bottom of the boiler having a temperature, in consequence, 200° below that of the top, the difference in length would be about one eight-hundredth, and, if confined by rigid abutments, iron so situated would be subject to a stress of twelve and a half tons per square inch. But in this case one part would yield by compression and the other by extension, and if they were to yield equally it would reduce the stress to six and a quarter tons. Actually, in this case, the lower fourth and upper three fourths would be more likely to act against each other, and the stress, if the boiler had no elasticity of form, would be about nine tons. Any elasticity of form—and boilers generally possess considerable—would still further reduce the strain, and it very frequently makes it insignificant.

It is thought, by some experienced engineers and other authorities, that many of the explosions known to have taken place, after inspection and test, at pressures lower than those of the test, are caused by the weakening action of unequal expansion, the stresses and strains produced in this manner being superadded to those due to simple pressure, against which latter the boiler might otherwise have been safe. Such effects may also be the final provocative to explosion when cold feed-water is pumped into a boiler, on getting up steam, or possibly, sometimes, when cooling off. It has even been asserted that an empty boiler has been ruptured by such changes of form consequent on building a light fire of shavings in a flue to start the scale. The Author has known of instances in which the girth-seams of large marine flue-boilers were ruptured along the line

of rivet-holes a distance of several feet by the introduction of a large volume of cold feed-water, when steam was up, but the engine at rest.

The differences of temperature on the two sides the sheet may be important. While it is true that the heat supplied by the furnace-gases is absorbed by the boiler to the same extent, practically, without much regard to the thickness of the plates of the boiler, it is a well-known fact that the resistance of iron to the flow of heat is so great that the effect of heat on the metal itself is seriously modified by the thickness of the sheet. Heavy plates "burn" away, projecting rivet-heads are destroyed, and the laps of heavy plates are especially liable to be thinned seriously where they are employed.

A variation of temperature of considerable range, and often recurring, frequently causes injury by hardening the metal of the boiler, making it brittle and liable to crack with change of form, and also produces the very change of form causing this cracking.

The experiments of Lt.-Col. Clark, R.A.,* show that great distortion may be thus produced. It is probably thus that iron and especially steel fireboxes so often crack, in consequence of a continual swelling of the metal under varying temperatures and the stresses so caused. This action, combined with oxidation, external and internal, sometimes makes the sheets and oftener the stays of a boiler remarkably weak and brittle; they sometimes become more like cast than wrought iron. The thicker the sheet, the more readily is it overheated and overstrained.

The extent to which alteration of form under pressure may go, with good material, before actual rupture, is illustrated by the following:† During the summer of 1868, a cylindrical boiler, made of $\frac{1}{4}$-inch steel plates, built at the Fort Pitt Iron Works, Pittsburg, was tested under authority of the government, with a view to determining the relative advantages of steel and iron as a material for navy boilers. When the pressure of cold water had reached 780 pounds, the girth of the boiler was found to

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* Proc. Royal Society, 1863; Journal Franklin Institute, 1863.

† *Iron Age*, Sept. 26, 1872.

have permanently increased $3\frac{5}{8}$ inches, and at 820 pounds rupture occurred.

Cases have been known in which a steel crown-sheet has become overheated, and has sagged down until, the tube-sheet going with it, a basin-shaped form has been produced, convex toward the fire, and yet no fracture produced, even when the pump was put on and the boiler filled up again under pressure.

291. The Management of the Steam-boiler, or, more correctly, its mismanagement, while in operation, and a neglect of proper supervision and inspection, may be considered, on the whole, the usual reason of explosion, as the deterioration of the boiler is the immediate cause; and this deterioration is almost invariably so gradual and so readily detected by intelligent and painstaking examinations that there is rarely any excuse for its resulting disastrously. A well-made boiler under good management and proper supervision may be considered as practically free from danger.

The person in direct charge of the boiler is usually a presumably experienced and trustworthy man. He should be thoroughly familiar with his business, generally intelligent, of good judgment, ready and prompt in emergencies, and absolutely reliable at all times. His first duty is to see that the boiler is full to the water-line, trusting only the gauge-cocks; he must keep constant watch of the furnaces, flues, and other surfaces subject to the action of the fire, and thus be certain that no injury is being done by overheating or sediment; he must keep the feed-apparatus in perfect working order, keep up the supply of water continuously and regularly, and see that the safety-valve is in good order at all times. Such careful management, conscientious inspection and cleaning, and repairing at proper intervals will insure safety.

To keep the safety-valve in good working order and to make certain that it is operative, provision should be made for opening it by hand, and it should be daily raised, before getting up steam, to the full height of its maximum lift.

Explosions of Gas sometimes precipitate steam-boiler explosions. Should the gases leaving the fuel and the furnace not be completely burned, but become so mingled in the flues as to

produce an explosive mixture, combustion finally occurring, the shock may be sufficient to cause rupture of the boiler, and, as has actually sometimes happened, its explosion. Sewer-gases have been known to find their way into an empty boiler through an open blow-off pipe, and have been exploded by the first light brought to the man-hole, and with serious damage to adjacent property. Mineral oils used to detach scale have caused similar dangerous and sometimes fatal explosions by the ignition of the mixture of their vapors and the air within the boiler. It is important that care be taken in using lights about boilers in such cases of application of mineral oils.

Explosions of gas within a boiler at work cannot occur; but the suggestion of the possibility of such an occurrence is often made. No decomposition of water can take place except a portion of the boiler is overheated; this happening, all the oxygen produced is absorbed by the iron, and no recombination can occur later, even were it possible for ignition to take place under the conditions producing decomposition.

The flooding of a boiler with water until it is filled to the steam-pipe or safety-valve may cause so serious a retardation of the outflow of the mingled fluids as to result in overpressure and great danger. Mr. W. L. Gold * gives the following instances, and the experience of the Author justifies fully his statement. The steam-pipe or the safety-valve cannot relieve a full boiler rapidly and safely.

First, a boiler 38 inches in diameter, two flues, shell ¼ inch Juniata iron, ruptured in the sheet a crack 9 inches long, steam-gauge indicating 60 pounds, safety-valve weighted at 80 pounds pressure. This rupture closed instantly; and if he had not seen it made, he might possibly have been surprised by an explosion, with water and steam in their normal condition, very shortly after. Second, a steam-drum (spanning a battery of five boilers) 30 inches in diameter. The blank-head forced (bulged) out 1½ inches, the stay-rods stretched, and the corner of the head-flange cracked one third around. Third, a vertical boiler, built especially to carry high pressure (safe running pressure

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* *Am. Manufacturer*, Feb. 1881.

150 pounds), the hand-hole and man-hole joints forced out past the flanges, the steam-pipe joints and union forced out, the packing in the engine-piston destroyed, and the engine generally racked, so as to be almost useless. Steam-pressure by gauge from 40 to 60 pounds; safety-valve weighted at 90 pounds.

Mr. Gold suggests that, as this is a not infrequent occurrence, many explosions may be simply the final act in the drama commenced by the feed-pump.

292. **Emergencies** must be met with a clear head and ready wit, with perfect coolness, and usually with both promptness and quickness of action. Every man employed about steam-boilers, as well as every engineer and every proprietor, should have carefully thought out the proper course to take in any and every emergency that he can conceive of as likely or possible to arise, and should have constantly in mind the means available for meeting it successfully. When the time comes to act, it is not always, or even often, possible to take time to study out the best thing to be done; action must be taken, on the instant, based on earlier thought or on either the intuition or the impulse of the moment.

"*Low-water*" presents perhaps the most common, as well as one of the most serious, of such emergencies. The instant it is detected, the effort must be made to check the fall to a lower level; the fire must be dampened, preferably by throwing on wet ashes, and the boiler allowed to cool down. Care should be taken that the safety-valve is not raised so as to produce a priming that might throw water over the overheated metal, and that no change is made in the working of either engine or boiler that shall produce foaming or an increased pressure. If, on examination, it is found that the water has not fallen below the level of either the crown-sheet or any other extended area of heating-surface, the pump may be put on with perfect safety; but if this certainty cannot be assured, the boiler should be cooled down completely, and carefully inspected and tested, and thoroughly repaired if injured. If no part of the exposed metal is heated to the red heat there is no danger, except from a rise in the water-level and flooding the hot iron. If any por-

tion should be red-hot, an additional danger is due to the steam-pressure, which should be reduced by continuing the engine in steady working while extinguishing the fire. If the safety-valve be touched at such a time, it should be handled very cautiously, allowing the steam to issue very steadily and in such quantities that the steam-gauge hand shows no fluctuation, while slowly falling. The damping of the fire with wet ashes will reduce the temperature and pressure very promptly and safely. The Author has experimentally performed this operation, standing by a large outside-fired tubular boiler while all the water was blown out, and then covering the fire. The pyrometer inserted in the boiler showed no elevation of temperature until all the water was gone, and the fire was then so promptly covered that the rise was but a few degrees, and the boiler was not injured. As it proved, there was not the slightest danger in that case; but with less promptness of action some danger might have arisen of injury to the boiler, although probably not of explosion.

Overheated plates, produced by sediment, or over-driving, resulting in the production of "pockets" or of cracks, are, virtually, cases of low-water, and the action taken should be the same. The boiler being safely cooled down, the injured plate should be replaced by a sound sheet, all sediment or scale carefully removed, and a recurrence of the causes of the accident effectively provided against.

Cracks, suddenly appearing in sheets exposed to the fire, or elsewhere, sometimes introduce a serious danger. The steps to be taken in such a case are the immediate opening of the safety-valve and reduction of steam-pressure as promptly and rapidly as possible, meantime quenching the fire and then cooling off the boiler and ascertaining the extent of the injury, and repairing it. In such a case, unless the crack is near the safety-valve itself, no fear need be entertained of too rapid discharge of the steam.

Blistered sheets should be treated precisely as in the cases preceding. It is not always possible to surmise the extent of the injury or the danger involved until steam is off and an examination can be made. It is not, however, absolutely neces-

sary to act as promptly as in the preceding cases; and where the blister is not large and is not extending, it is sometimes perfectly allowable to await a convenient time for blowing off steam and making repairs.

An inoperative safety-valve, either stuck fast, or too small to discharge all the steam made, or to keep the pressure down to a safe point, produces one of the most trying of all known emergencies. In such a case steam should be worked off through the engine, if possible, and discharged through any valves available, through the gauge-cocks, or even through a few scattered rivet-holes, out of which the rivets may be knocked on the instant; the fire being meantime checked by the damper or by free use of water. The throwing of water into a furnace is often a somewhat hazardous operation, however, and if necessary, should be performed with some caution, to avoid risk of injury of either the person attempting it, or of the boiler. The use of wet ashes is preferable. In all cases in which it is to be attempted to reduce the rate of generation of heat, closing the ash-pit doors as well as opening the fire-doors will be of service by checking the passage of hot air from below and accelerating the influx of cold air above the grate; but the closing of the ash-pit involves, with a hot fire, some risk of melting down the grates.

293. The Results of Explosions of steam-boilers, in spreading destruction and death in all directions, are so familiar as scarcely to require illustration; but a few instances may be described as examples in which the stored energy of various types of boiler has been set free with tremendous and impressive effect.

Referring to the table in § 269, and to case No. 1: The explosion of a boiler of this form and of the proportions here given, in the year 1843, in the establishment of Messrs. R. L. Thurston & Co., at Providence, R. I., is well remembered by the Author. The boiler-house was entirely destroyed, the main building seriously damaged, and a large expense was incurred in the purchase of new tools to replace those destroyed. No lives were lost, as the explosion fortunately occurred after the workmen had left the building. A similar explosion of a boiler of this

size occurred some years later, within sight of the Author, which drove one end of the exploding boiler through a 16-inch wall, and several hundred feet through the air, cutting off an elm-tree high above the ground, where it measured 9 inches in diameter, partly destroying a house in its further flight, and fell in the street beyond, where it was found hot and dry immediately after striking the earth. Long after the Author reached the spot, although a heavy rain was falling, it was too hot to be touched, and was finally, some time later, cooled off by a stream of water from a hose, in order that it might be moved and inspected. It had been overheated, in consequence of low-water, and cold feed-water had then been turned into it. The boiler was in good order, but four years old, and was considered safe for 110 pounds. The attendant was seriously injured, and a pedestrian passing at the instant of the explosion was buried in the ruins of the falling walls and killed. The energy of this explosion was very much less than that stored in the boiler when in regular work:

A boiler of class No. 3, which the Author was called upon to inspect after explosion, had formed one of a "battery" of ten or twelve, and was set next the outside boiler of the lot. Its explosion threw the latter entirely out of the boiler-house into an adjoining yard, displaced the boiler on the opposite side, and demolished the boiler-house completely. The exploding boiler was torn into many pieces. The shell was torn into a helical ribbon, which was unwound from end to end. The furnace-end of the boiler flew across the space in front of its house, tore down the side of a "kier-house," and demolished the kiers, nearly killing the kier-house attendant, who was standing between two kiers. The opposite end of the boiler was thrown through the air, describing a trajectory having an altitude of fifty feet and a range of several hundred, doing much damage to property *en route*, finally landing in a neighboring field. The furnace front was found by the Author on the top of a hill, a quarter of a mile, nearly, from the boiler-house. The attendant, who was on the top of the boiler at the instant of the explosion, opening a steam-connection to relieve the boiler, then con-

taining an excess of steam and a deficiency of water, was thrown over the roof of the mill, and his body was picked up in the field on the other side, and carried away in a packing-box measuring about two feet on each side. The cause was low-water and consequent overheating, and the introduction of water without first hauling fires and cooling down. Both this boiler and the plain cylinder are thus seen to have a projectile effect only to be compared to that of ordnance.

The violence of the explosion of the locomotive boiler is naturally most terrible, exceeding, as it does, that of ordnance fired with a charge of 150 pounds of powder of best quality, or perhaps 250 pounds of ordinary quality fired in the usual way.* On the occasion of such an explosion which the Author was called upon to investigate, in the course of his professional practice, the engine was hauling a train of coal cars weighing about 1000 tons. The steam had been shut off from the cylinders a few minutes before, as the train passed over the crest of an incline and started down the hill, and the throttle again opened a few moments before the accident. The explosion killed the engineer, the fireman, and a brakeman, tore the firebox to pieces, threw the engine from the track, turning it completely around, broke up the running parts of the machinery, and made very complete destruction of the whole engine. There was no indication that the Author could detect of low-water; and he attributed the accident to weakening of the fire box sheets at the lower parts of the water-legs by corrosion. The bodies of the engineer and fireman were found several hundred feet from the wreck, the former among the branches of a tree by the side of the track. This violence of projection of smaller masses would seem to indicate the concentration of the energy of the heat stored in the boiler, when converted into mechanical energy, upon the front of the boiler, and its application largely to the impulsion of adjacent bodies. The range of projection was,

* The theoretical effect of good gunpowder is about 500 foot tons per pound (340 tonne-metres per kilogramme), according to Noble and Abel.

in one case, fully equal to the calculated range. The energy expended is here nearly the full amount calculated.

Figs. 157, 158, 159, 160 illustrate the explosion of two large boilers which produced very disastrous effects,* killing the attendant and destroying the boiler-house and other property. These boilers were horizontal, internally-fired, drop-flue boilers, seven feet diameter and twenty-one feet long, the shells single-riveted, originally five sixteenths of an inch thick.

FIG. 157.—EXPLOSION OF BOILERS AT BROOKLYN, N. Y.

The two exploded boilers were made twenty-one years before the explosion, and worked, as their makers intended, at about thirty pounds per square inch, till about twenty months before the explosion, at which time additional power was required, and the pressure was increased to and limited at fifty pounds.

A third boiler did not explode, but was thrown about fifty feet out of its bed.

FIG. 158.—POSITION OF THE THREE BOILERS AFTER THE EXPLOSION.

A few minutes before noon, while the engine was running at the usual speed, the steam-gauge indicating forty-seven pounds

* *Scientific American*, May 20, 1882.

pressure, and the water-gauges showing the usual amount of water, the middle one exploded: the shell burst open, and was nearly all stripped off. The remainder of the boiler was thrown high in the air.

While this boiler was in the air, No. 1, the left-hand boiler, having been forcibly struck by parts of No. 2, also gave way so

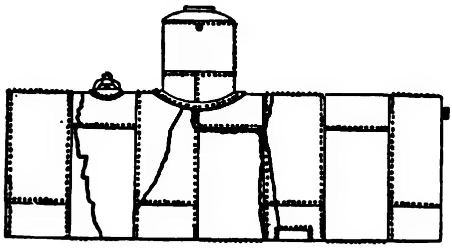


FIG. 159.—INITIAL RUPTURE.

that its main portion was projected horizontally to the front, arriving at the front wall of the building in time to fall under No. 2, as shown in Fig. 158. The most probable method of rupture is indicated in Fig. 159, as the line *AB* separates a ring of plates which was found folded together beneath the pile of *dé-*

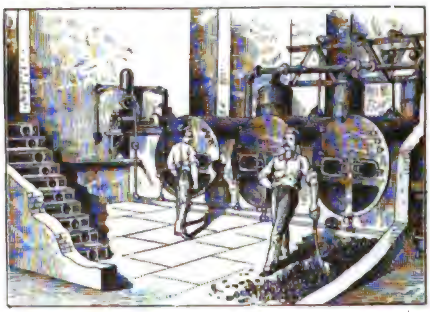


FIG. 160.—INTERIOR OF BOILER-HOUSE PRIOR TO THE EXPLOSION.

bris. If the initial break had been at some point on the bottom, this belt of plates would have been thrown upward and flattened, instead of downward, where it was thrown by the flood of water from No. 1 boiler.

The third boiler was raised from its bed by the issuing water, and thrown about fifty feet to the right of its original position.

These two boilers contained probably more than fourteen tons of water, which had a temperature due to forty-seven

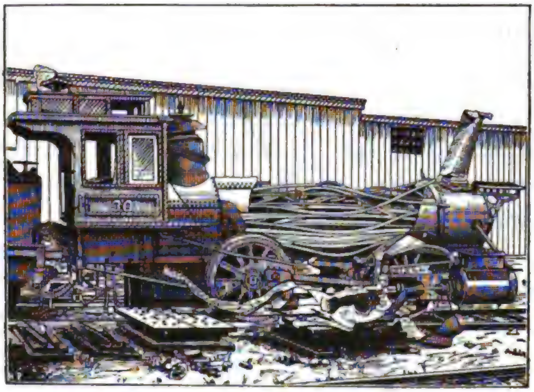


FIG. 161.—EXPLODED LOCOMOTIVE.

pounds of steam, and the effect of its sudden liberation was equal that of several hundred pounds of exploded gunpowder.

The terrible wreck usually consequent upon the explosion

FIG. 162.—TUBES OF AN EXPLODED BOILER.

of a locomotive boiler is well illustrated in the accompanying engraving, which represents the results of such an explosion on the Fitchburg Railway, August 13, 1877; while the havoc

wrought among the tubes on such occasions is as strikingly illustrated in Fig. 162.

In the case of an explosion of a locomotive investigated by a commission of which the Author was a member, the train was moving slowly when the boiler exploded with a loud report; the locomotive was turned completely over backward, carrying with it and burying the fireman beneath the ruins.

Nothing could at first be found of the engineer. Parties searched for long distances about the wreck for signs of the unfortunate man, but it was not until next morning that his body was found. It was discovered lying in the woods, seven hundred feet away from the locomotive.

The locomotive was completely demolished, and every part of the machinery was twisted or broken into pieces. The track was torn up for some distance, and rails were bent like coils of rope. The firebox of the locomotive was hurled from its position and broken into many pieces. A large piece weighing many hundred pounds was carried five hundred feet. The dome and sand-box were thrown an eighth of a mile into the adjacent river. The wheels of the engine were torn off, and no one piece of the cab was discovered. The engineer bore an excellent reputation as being a careful man, always carrying a large supply of water. The engine was one of approved make, and had been in use for fifteen years. It had just come from the repair-shop. A new firebox had been put in three years before, and the boiler was thoroughly examined about six weeks earlier. The iron was in many cases twisted and bent into shapeless rolls. The point of rupture was apparently in the left-hand lower corner of outside shell of the firebox. The cause was variously assigned as a percussion or "fulminating" action due to overheated iron and to certain defective portions of the firebox. The latter was probably the true cause.

The following may be taken as another illustration of the tremendous effects of explosion at usual working pressure, with an ample supply of water: A boiler of the locomotive type was constructed for use in a small steamer. Its shell was of iron, 4 feet in diameter, and $\frac{5}{16}$ths inch thick. It was "tested" by filling with water and raising steam. It exploded with the

safety-valve set at 120 pounds pressure per square inch, blowing freely, although held down by the man in charge, and killed and injured several people. The hiss of steam escaping from the initial rupture was heard an instant before the explosion. The boiler was turned end for end, and the firebox torn from the boiler in two pieces, one being carried to a distance of about 500 feet and imbedded in the mud of a canal-bed; the other portion, weighing about 4800 pounds, was carried a distance of between 400 and 500 feet, and crashed into the side of a building filled with sash, blinds, and doors piled closely together. This piece of iron comprised the firebox, the dome, and the end of the boiler, and was straightened into a piece 30 feet long and four feet wide. This piece is said to have rushed through the air with a whirling motion until it struck the building. It cut the side of the building and beams and rafters like straws, pushing the front of the building forward several feet. Fragments of the boiler were found at many points considerably distant from the scene of the explosion, and in many places windows were shattered by the concussion.

The shell of the boiler was reversed by the force of the explosion, with such force that one end was buried four feet in the road-bed. All the flues remained in the boiler, one end of which was torn from them while the other remained in place. At the instant of the explosion the air for many feet in every direction was filled with flying fragments, many of them being thrown to a great height.

In one case coming under the observation of the Author, a locomotive set as a stationary boiler gave way in the firebox, and let out the water and steam, but injured no one. The rent was about twelve inches long and eight inches wide. The iron in that place was weakened by corrosion, otherwise the boiler was in good condition. Repairs were immediately commenced and the boiler was ready for use next day. Had this rent occurred at or above the water-level, it is very possible that an explosion may have resulted, in the manner suggested by Clark and Colburn.

In an explosion of a tubular boiler at Dayton, O., Oct. 25,

1881,* by which several lives and much property were destroyed, the rupture started along the lap *AB* in the figure, and was evidently due to the furrowing which had been there, in some way, produced. The boiler was less than a year old, and was reported to be of good material and workmanship. The longitudinal seams were double-riveted, and it is very possible that the stiffness thus produced along their lines may have so localized the strains due to alterations of form as to have led to this fatal result, aided by the action of the calking-tool, the

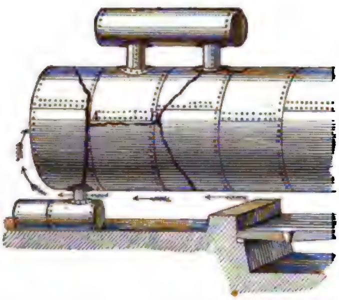


FIG. 163.—INITIAL RUPTURE; "GROOVING."

FIG. 164.—BOILER-EXPLOSION AT DAYTON, OHIO.

marks of which along the line at which the crack gradually worked through the sheet were plainly visible. The boiler had, when first set in place, been tested to 140 pounds; the explosion occurred at probably less than 80.

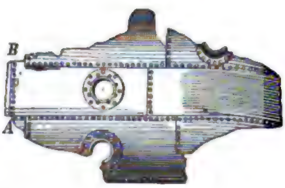


FIG. 165.—GIRDLE OF PLATES TORN FROM NO. 2 BOILER.

A strip of plates, as in Fig. 165, was torn from the boiler, separating it into two parts, as seen in the two succeeding figures, and throwing them apart with all the force due to a

* *Scientific American*, Dec. 17, 1881.

hundred millions of foot-pounds of available stored heat-energy, and entirely destroying the house in which they were set.

In a case of explosion at Pittsburg, Pa., in December, 1881, a battery of flue-boilers was connected, as seen in Fig.

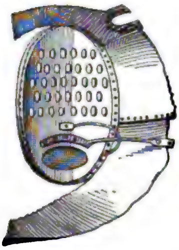


FIG. 166a. REAR END OF BOILER AFTER EXPLOSION.

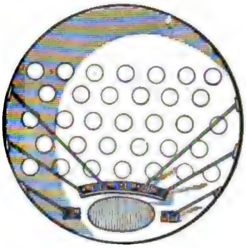


FIG. 166b. REAR END OF BOILER BEFORE EXPLOSION.

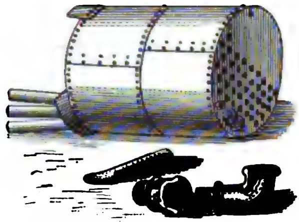
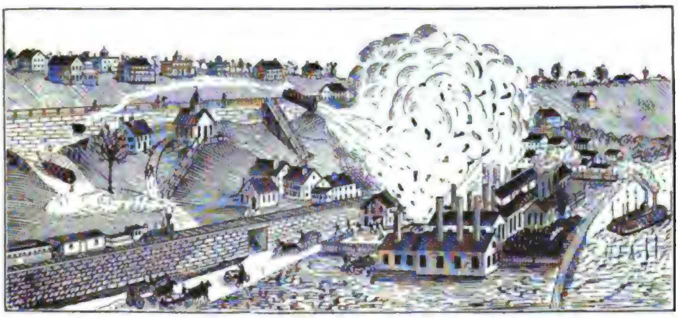


FIG. 167.—FRONT END OF BOILER AFTER EXPLOSION.

169, by steam-drums above the nearer two and mud-drums beneath all three. The steam-pressure was not far from 125 pounds per square inch at the time of the accident. The boilers



5.—Principal part of No. 5 boiler, thrown over the church on the bluff. 6.—Principal part of No. 6 boiler.

FIG. 168.—EXPLOSION OF TWO STEAM-BOILERS AT PITTSBURG, PA.

were fifteen years old, but had been tested to 170 pounds two years earlier, and allowed to work at 120 pounds, although they had been repeatedly patched and repaired.* The rules of the

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* *Scientific American*, Feb. 4, 1882.

insurance companies would have allowed but one half this pressure.

The strains produced by the changes of form with varying temperature of feed-water, and by the action of the new iron of the patches on the older and corroded parts of the boiler, started cracks which gradually weakened them, and finally led

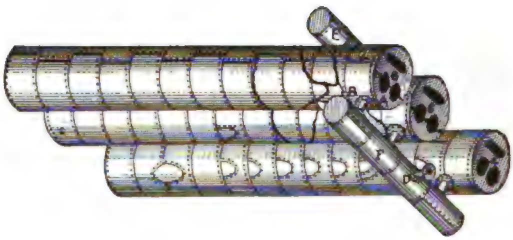

FIG. 169.—UNDER SIDES OF BOILERS.

to a rupture along the worst line of injury, *AB*, in the preceding figure, opening the course of plates at *a*, and tearing it out as in the next figure, in which *AB* is the line of initial fracture.

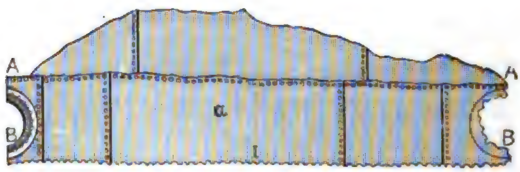

FIG. 170.—COURSE OF PLATES DETACHED.

The destruction of this (No. 6) boiler was accompanied by the disruption of that next it (No. 5), which was also in about as dangerous condition. The available energy of the explosion was about 250,000,000 foot-pounds, and the damage produced was proportional to this enormous power. One boiler (No. 5) was thrown across the road and over a church; the other (No. 6) was thrown to one side, partially destroying neighboring buildings. The boiler-house was entirely destroyed. The third boiler remained unexploded, and was found a little out of place and nearly full of water.

According to the observer furnishing these particulars, the conclusions are inevitable:

(1) That the two boilers exploded in succession so quickly as to be practically simultaneous, beginning at the weak line *AB* of No. 6 boiler.

(2) That they contained an ample supply of water.

(3) That the pressure was too great for boilers of their size and condition.

(4) That the use of cold feed-water hastened the deteriora-

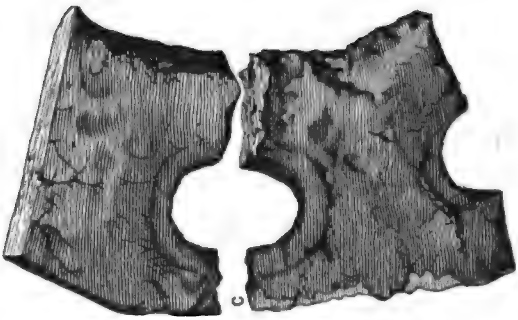

FIG. 171.—PIECE OF PATCH.

tion of poor iron, causing cracks and leaks, by which external corrosion was produced, and that the energy stored in the water of these boilers caused all the destruction observed.

It is always to be strongly recommended that regular and continuous feeding of hot water be practised; and that the greatest care be exercised by inspectors and those in charge of steam-boilers in searching for and immediately repairing dangerous defects.

The last figure is an excellent illustration of the appearance of iron when thus corroded and cracked. At *C* the crack was old, and partly filled up with lime-scale.

The explosion of the upright tubular boiler is usually consequent upon some injury of its furnace, either by collapse or by the yielding of the tube-sheet to excessive pressure. The result is commonly the projection of the boiler upward like a rocket, and is rarely accompanied by much destruction of property laterally. A typical case of this kind is that of an

explosion occurring at Norwich, Connecticut, December 23, 1881, of which the following is a brief account:*

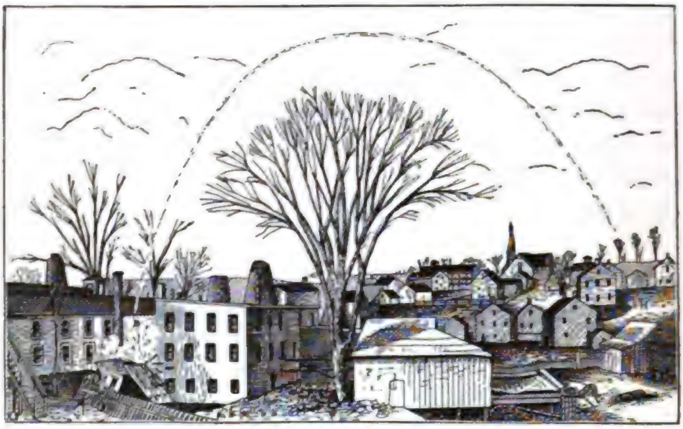

FIG. 172.—EXPLOSION OF AN UPRIGHT BOILER.

Fig. 173 represents the location of the boiler and engine immediately before the explosion. The explosion took place, as shown in figure, by the yielding of the lower tube-plate of the boiler. This boiler was three feet in diameter and seven feet high, and was four years old. The boiler was made of five-sixteenths iron throughout. It contained sixty tubes, two inches in diameter, five feet long, which were set with a Prosser expander, and were beaded over as usual. The upper tube-head was flush with the top of the shell, and the lower, forming the crown of the furnace, was about two feet above the grates and the base of the shell, and was flanged upon the inner surface of the furnace. There was a safety-plug in the lower tube-head, which was not melted out, although, as is often the case when

FIG. 173.—BOILER-ROOM BEFORE THE EXPLOSION.

* *Scientific American*, Jan. 14, 1882.

these plugs are so near the fire, a portion of the lower part of the fusible filling had disappeared.

The working pressure was sixty pounds per square inch, and the explosion probably took place at or a little below this pressure, throwing the boiler through the roof and high over a group of buildings, and a tall tree close by, finally burying itself half its diameter in the frozen ground. There had been leak in the tubes, and four had been plugged. There was a crack in the upper head near the centre, which extended between three tubes. From this crack steam escaped, and the water had settled upon the surrounding surface of the tube-head and the tube-ends. The result was to reduce the five-sixteenths plate to less than a quarter of an inch in thickness, and the tube-ends to the thickness of writing-paper. The lower tube-ends had suffered still

FIG. 174.—YIELDING TUBE-SHEET.

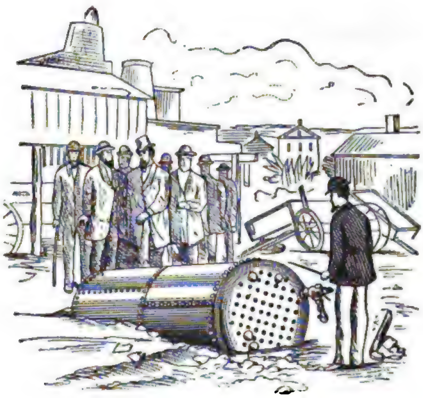

FIG. 175.—THE EXPLODED BOILER.

more from leaks, and were as thin as paper, and afforded no adequate support to the head. The pressure consequently forced the lower head down, opening fifty or more holes two inches diameter, from which the fluid contents of the boiler issued at a high velocity and the whole boiler became a great rocket, weighing about two thousand pounds.

One life was destroyed by this explosion and a considerable amount of property.

An explosion which occurred at Jersey City, N. J., some years ago, illustrates at once the dangers of low-water and of a safety-valve rusted fast. As reported at the time,* "The boiler was of the locomotive type, having a dome upon the top. The engineer upon the morning of the explosion lighted the fire in the boiler, and shortly afterwards was called away, leaving the boiler in charge of his nephew, who was young and inexperienced in the handling of steam. After putting fresh coal in the furnace he was called away by one of the owners of the dock to assist at some outside duty. Upon his return he saw the seams of the boiler opening, and attempted to open the furnace-door, but was unable, owing to the excess of pressure of steam within the boiler which had caused the head to change its shape. A few moments afterwards the explosion occurred, the firebox being thrown downwards, the top of the shell and crown-sheet upwards, while the cylinder part shot directly up the street. It struck the ground about 400 feet from its original position, demolished a fire-hydrant, several trucks, trees, and a horse, and, spinning end for end, came to rest by the side of a truck, which it destroyed, about 642 feet from its starting-point. Subsequent investigation revealed the fact that the boiler was not properly supplied with water. A portion of the crown-sheet which we examined showed conclusively that near the flues it was red-hot. We also examined the safety-valve, which was of the wing pattern, having a lever and weight. This valve was so firmly corroded to its seat that it could not be removed, and

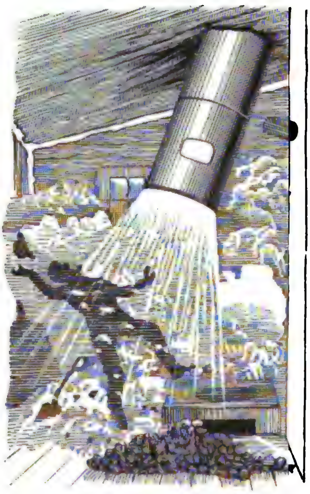

FIG. 176.—THE EXPLOSION.

* *Am. Machinist*, Oct. 1, 1881.

the stem was also corroded fast. The whole secret of this explosion is that the boiler was short of water, and an excessively high pressure of steam was raised to an unknown point, which, without relief, acquiring sufficient force, tore the boiler to pieces."

The valve was found, and, being placed in a testing-machine then under the charge of the Author, at the Stevens Institute of Technology, was only started by a pressure of a ton and a half,* while nearly two tons was required to move it observably.

Change of form with varying pressures and temperatures sometimes produces most unexpected defects. It has been observed that many locomotive boilers stayed as in the figure† give way at the side, in the manner here exhibited. Investigation shows that in these cases the tying of the furnace-crowns to the shell by the system of staying illustrated, and the continual rising and falling of the furnace relatively to the shell, is very apt to cause a buckling of the outside sheet along the horizontal seam, which finally yields. This buckling and straightening of the sheet goes on until a crack or a furrow is formed along the lap nearest the most rigid brace, and, when this has cut deeply enough, the side of the boiler opens, often, the whole length of the furnace, the explosion doing an amount of damage which is determined by the steam-pressure, the quantity of energy stored, and the extent of the rupture.

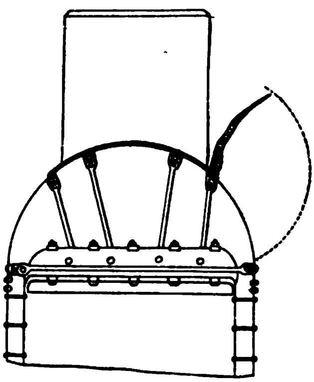

FIG. 177.—FAULTY STAYING.

In these cases, either the crown-bars over the furnace or the stays should alone have been used; their use together is objectionable. Of the two systems, probably the first is the safer in such boilers.

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* *Am. Machinist*, Oct. 22, 1881.

† *Locomotive*, Jan. 1, 1880.

The appearance of a collapsed flue is seen in the two succeeding figures, which represent the results of experiments made by the U. S. Commission appointed to investigate the causes of

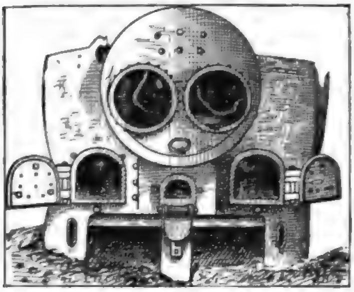

FIG. 178.—COLLAPSED FLUES.

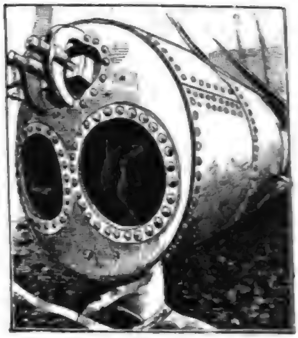

FIG. 179.—COLLAPSED FLUES.

explosions of steam-boilers. In neither case did the boiler move far from its original position. Collapsed flues rarely cause extensive destruction of property.

The explosion of a rotary rag-boiler, receiving steam from

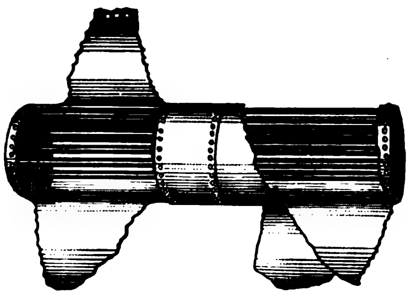

FIG. 180.—AN EXPLODED BOILER.

steam-boilers at a distance, which took place at Paterson, N. J., wrecked the mill, destroyed a part of an adjacent establishment, and caused serious loss of life and property. The disaster was due to weakening of the boiler by corrosion, but, notwithstanding its reduced strength, the shock of the explosion was felt and was heard throughout the city, and heavy plate-glass windows were broken at a considerable distance from the scene of the accident. Explosions of this kind show the fallacy

of many of the absurd and mischievous "theories" which have been prevalent in regard to explosions.

Where the iron or steel used in the construction of the boiler is of good quality, strong, uniform, and ductile, the smaller torn parts of an exploded boiler may not break away from the main body; such a case is illustrated in the last figure (180), which represents the effect of an explosion of a new boiler from a cause not ascertained. The boiler was 15 feet long by 4 feet diameter, with 38 four-inch flues. Both heads remained on the flues, but the shell of the boiler burst along the rivet-holes nearly all around both heads, as shown in the engraving.

294. **Experimental Investigations** of the causes and methods of steam-boiler explosions have been occasionally attempted. One of the earliest and most systematic, as well as fruitful, was that of a committee of the Franklin Institute, the results of which were reported to the Secretary of the U. S. Treasury early in 1836.

This committee proposed by experiment—

I. To ascertain whether, on relieving water heated to, or above, the boiling-point, from pressure, any commotion is produced in the fluid.

To determine the value of glass-gauges and gauge-cocks.

The investigation of the question whether the elasticity of steam within a boiler may be increased by the projection of foam upon the heated sides, more than it is diminished by the opening made.

II. To repeat the experiments of Klaproth on the conversion of water into steam by highly heated metal, and to make others, calculated to show whether, under any circumstances, intensely heated metal can produce, suddenly, great quantities of highly elastic steam.

To directly experiment in relation to the production of highly elastic steam in a boiler heated to high temperature.

III. To ascertain whether intensely heated and unsaturated steam can, by the projection of water into it, produce highly elastic vapor.

IV. When steam surcharged with heat is produced in a

boiler, and is in contact with water, does it remain surcharged, or change its density and temperature?

V. To test, by experiment, the efficacy of plates, etc., of fusible metal, as a means of preventing the undue heating of a boiler or its contents.

(1) Ordinary fusible plates and plugs.

(2) Fusible metal, inclosed in tubes.

(3) Tables of the fusing-points of certain alloys.

VI. To repeat the experiments of Klaproth, etc.

(1) Temperature of maximum vaporization of copper and iron under different circumstances.

(2) The extension to practice, by the introduction of different quantities of water, under different circumstances of the metals.

VII. To determine by actual experiment whether any permanently elastic fluids are produced within a boiler when the metal becomes intensely heated.

VIII. To observe accurately the sort of bursting produced by a gradual increase of pressure, within cylinders of iron and copper.

IX. To repeat Perkins' experiment, and ascertain whether the repulsion stated by him to exist between the particles of intensely heated iron and steam be general, and to measure, if possible, the extent of this repulsion, with a view to determine the influence it may have on safety-valves.

X. To ascertain whether cases may really occur when the safety-valve, loaded with a certain weight, remains stationary, while the confined steam acquires a higher elastic force than that which would, from calculation, appear necessary to overcome the weight of the valve.

XI. To ascertain by experiment the effects of deposits in boilers.

XII. Investigation of the relation of temperature and pressure of steam at ordinary working pressures.

It is only necessary here to state that the results proved—

(1) That relieving pressure even slightly produced great commotion in the water, and considerably relieving it caused

the violent ejection of water as well as steam through the opening by which the pressure was reduced.

(2) That under similar conditions pressure invariably diminished.

(3) That the injection of water upon the heated surfaces of the experimental boiler produced a sudden and considerable rise of pressure.

(4) That the injection of water into superheated steam reduced its pressure in all cases noted.

(5) That superheated steam may remain in contact with water a long time (two hours in the experiments tried) without becoming saturated.

(6) That fusible plugs, as then constructed, were unreliable, and the fusing-points of various alloys were determined.

(7) That the temperature of maximum vaporization of water is lowered by smoothness of surfaces; that of iron is thirty or forty degrees higher than that of copper, while the time required is one half as great with copper; that the temperature of maximum vaporization, for oxidized iron, or for highly oxidized copper, is about 350° F., and that the repulsion between the metal and the water is perfect at from twenty to forty degrees above the temperature of maximum vaporization.

(8) That no hydrogen was liberated by throwing water or steam upon heated surfaces of the boiler; that the water was not decomposed, and that air cannot occur in any appreciable quantity in a steam-boiler at work.

(9) That "*all the circumstances attending the most violent explosions may occur without a sudden increase of pressure within a boiler*," the explosion being produced by gradually accumulated pressure.

(10) That but a small part of water, highly heated, can expand into steam, if suddenly relieved of pressure.

(11) That water can be heated to very high temperature only under intensely high pressure.

(12) That steam-pressure may rise even after it has raised the safety-valve.

Unpublished experiments recently made by Professor Mason at the Rensselaer Polytechnic Institute strongly confirm the so-

called "geyser theory" of Messrs. Clark and Colburn. In these experiments a number of miniature boilers were constructed, and were exploded by a gradually produced excess of pressure, and in such manner as to test this theory. The first of these boilers, when exploded, produced such an effect, blowing out windows and shaking down the ceiling of the laboratory as effectually to dispose of the idea prevalent among certain classes of engineers that a true explosion could only be caused by low-water and overheated plates. Another boiler was so set that, the rear end being lower than the front, the quantity of water acting by percussion, according to the Clark theory, was much greater at the one end than at the other. The consequence was that while the one end was broken into many pieces, that in which there was least water was simply torn from the mass of the boiler and was itself unbroken. In one of this series of experiments the boiler was broken into more than a hundred pieces, although made of drawn brass—a material far less liable, ordinarily, to be thus shattered than iron or steel. The second of the above-described experiments appears to the Author a very nearly crucial test and proof of the theory of Messrs. Clark and Colburn.

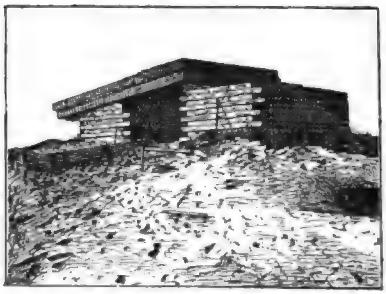

FIG. 181.—BOMB-PROOF.

In the work of investigation involving the explosion of steam-boilers it is usually necessary to provide a safe retreat for the observers, from which to watch the progress of the experiment, and from which to read the steam-gauge, to watch the water-level, and to take the readings of the thermometers or pyrometers.

The illustration represents the structure, composed of heavy timber, and partially underground, used at the testing-ground at Sandy Hook, by the U. S. Commission of 1873–6.

These experiments were projected and conducted by Mr. Francis B. Stevens of Hoboken, and at the request of Mr. S. the United Railroad Companies of New Jersey appropriated the sum of ten thousand dollars to enable Mr. Stevens to enter upon a preliminary series of experiments. They at the same time invited other railroads and owners of steam-boilers to co-operate with them, and offered the use of their shops for any work that might be considered necessary or desirable during the progress of the work; no such aid was, however, received.

Several old boilers had recently been taken out of the steamers of the United Companies. These were subjected to hydrostatic pressure until rupture occurred, were repaired and again ruptured several times each, thus detecting and strengthening their weakest spots, and finally leaving them much stronger than when taken from the boats. The points at which fracture occurred and the character of the break were noted carefully at each trial.

After the weak spots had thus been felt out and strengthened, the boilers were taken, with the permission of the War Department, to the United States reservation at Sandy Hook, at the entrance to New York harbor, and were there set up in a large inclosure which had been prepared to receive them, and the four old steamboat-boilers above referred to, together with five new boilers built for the occasion, were placed in their respective positions without having been in any way injured.

Finally, on the 22d and 23d of November, the experiments to be described were made.

The first boiler attacked was an ordinary "single return-flue boiler."

The cylindrical portion of the shell was 6 feet 6 inches diameter, 20 feet 4 inches long, and of iron a full quarter inch thick. The total length of the boiler was 28 feet: the steam chimney was 4 feet diameter, 10½ feet high, and its flue was 32 inches diameter. The two furnaces were 7 feet long, with flat arches. There were ten lower flues, two of 16 and eight of 9

inches diameter, and all were 15 feet 9 inches long; there were twelve upper flues, 8½ inches in diameter, and 22 feet long. The total grate-surface was 38½ square feet, heating-surface 1350 square feet. The water-spaces were 4 inches wide, and

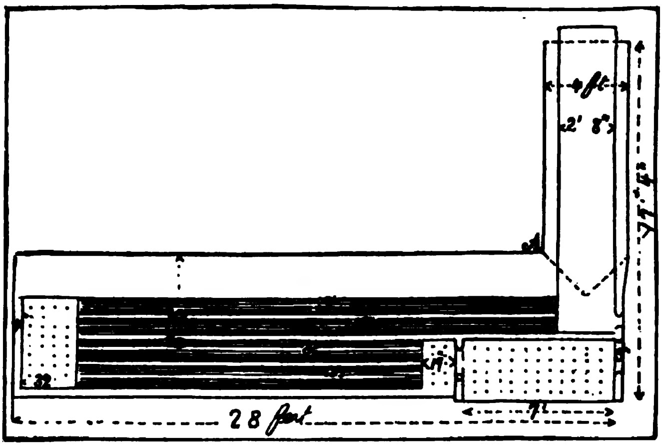

FIG. 182.—MARINE BOILER.

the flat surfaces were stayed by screw stay-bolts at intervals of 7 inches. The boiler was thirteen years old, and had been allowed 40 pounds pressure.

The upper portion of the boiler, when inspected before the experiment, seemed to be in good order. The girth-seams on the under side of the cylindrical portion had given way, and had all been patched before it was taken out of the boat. The water-legs had been considerably corroded.

In September this boiler had been subjected to hydrostatic pressure, giving way by the pulling through of stay-bolts at 66 pounds per square inch. It was repaired, and afterward, at Sandy Hook, was tested without fracture to 82 pounds, and still later bore a steam-pressure of 60 pounds per square inch.

On its final trial, November 22d, a heavy wood fire was built in the furnaces, the water standing 12 inches deep over the flues, and, when steam began to rise above 50 pounds, the whole party retired to the gauges, which were placed about

250 feet from the inclosure. The notes of pressures and times were taken as follows:

TIME.	PRESSURE.	TIME.	PRESSURE.	TIME.	PRESSURE.	TIME.	PRESSURE.
2.00 P.M.	58 lbs.	2.15 P.M.	87 lbs.	2.25 P.M.	91¼ lbs.	2.40 P.M.	91½ lbs.
2.05 "	68 "	2.20 "	91¼ "	2.30 "	91 "	2.45 "	91 "
2.10 "	78 "	2.23 "	93 "	2.35 "	91½ "	2.50 "	90 "

The pressure rose rapidly until it reached about 90 pounds,* when leaks began to appear in all parts of the boiler; and at 93 pounds a rent at (*A*, Fig. 182) the lower part of the steam-chimney where it joins the shell becoming quite considerable, and other leaks of less extent enlarging, the steam passed off

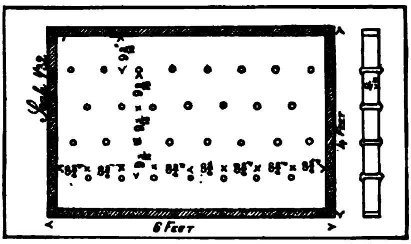

FIG. 183.—STAYED WATER-SPACE.

more rapidly than it was formed. The pressure then slowly diminishing, the workmen extinguished the fires by throwing earth upon them, and the experiment thus ended.

The second experiment was made with a small boiler (Fig. 183), which had been constructed to determine the probable strength of the stayed surface of a marine boiler. It had the form of a square box, 6 feet long, 4 feet high, and 4 inches thick. Its sides were $\frac{5}{16}$ inch thick, of the "best flange firebox" iron. The water-space was $3\frac{3}{8}$ inches wide. The rivets along the edges were $\frac{3}{4}$ inch diameter, spaced 2 inches apart. The two

* The ultimate strength of this boiler, when new, was probably equal to about double this pressure.

sides were held together by screw stay-bolts, spaced $8\frac{3}{4}$ and $9\frac{3}{16}$ inches, and their ends were slightly riveted over, precisely copying the distribution and workmanship of a water-leg of an ordinary marine boiler. It had been tested to 138 pounds pressure. This slab was set in brickwork, about five sixths of its capacity occupied by water, and fires built on both sides. Pressure rose as shown by the following extract from the note-book of the Author:

TIME.	PRESSURE.	TIME.	PRESSURE.	TIME.	PRESSURE.	TIME.	PRESSURE.
3.18 P.M.	0 lbs.	3.28 P.M.	20 lbs.	3.37 P.M.	54 lbs.	3.46 P.M.	117 lbs.
3.20 "	4 "	3.29 "	23 "	3.38 "	58 "	3.47 "	126 "
3.21 "	5 "	3.30 "	27 "	3 39 "	65 "	3.48 "	135 "
3.22 "	7 "	3.31 "	30 "	3.40 "	72 "	3.49 "	147 "
3.23 "	9 "	3.32 "	34 "	3.41 "	78 "	3.50 "	160 "
3.24 "	11 "	3 33 "	38 "	3.42 "	86 "	3.51 "	165 "
3.25 "	13 "	3.34 "	44 "	3.43 "	94 "	Exploded.	
3.26 "	15 "	3.35 "	49 "	3.44 "	100 "		
3.27 "	18 "	3.36 "	51 "	3.45 "	110 "		

At a pressure of slightly above 165, and probably at about 167 pounds, a violent explosion took place. The brickwork of the furnace was thrown in every direction, a portion of it rising high in the air and falling among the spectators near the gauges; the sides of the exploded vessel were thrown in opposite directions with immense force, one of them tearing down the high fence at one side of the inclosure, and falling at a considerable distance away in the adjacent field; the other part struck one of the large boilers near it, cutting a large hole, and thence glanced off, falling a short distance beyond.

Both sides were stretched very considerably, assuming a dished form of 8 or 9 inches depth, and all of the stay-bolts drew out of the sheets without fracture and without even stripping the thread of either the external or the internal screw; this effect was due partly to the great extension of the metal, which enlarged the holes, and partly to a rolling out of the metal as the bolts drew from their sockets in the sheet.

Lines of uniform extension seemed to be indicated by a peculiar set of curved lines cutting the surface scale of oxide on

the inner surface of each sheet, and resembling closely the lines of magnetic force called by physicists magnetic spectra. These curious markings surrounded all of the stay-bolt holes.

The third experiment took place at a later date. The boiler selected on this occasion was a "return-tubular boiler" with no lower flues, the furnace and combustion-chamber occupying the whole lower part. Its surface extended the whole width of the boiler, thus giving an immense crown-sheet.

This boiler was built in 1845, and had been at work *twenty-five years;* when taken out, the inspector's certificate allowed 30 pounds of steam. In September it was subjected to hydrostatic pressure, which at 42 pounds broke a brace in the crown-sheets, and at 60 pounds 12 of the braces over the furnace gave way, and allowed so free an escape of water as to prevent the attainment of a higher pressure. The broken parts were carefully repaired, and the boiler again tested at Sandy Hook to 59 pounds, which was borne without injury, and afterward a steam-pressure of 45 pounds left it still uninjured. At the final experiment the water-level was raised to the height of 15 inches above the tubes, and it there remained to the end. The fire was built, as in the previous experiments, with as much wood as would burn freely in the furnace, and the record of pressures was as follows:

TIME.	PRESSURE.	TIME.	PRESSURE.	TIME.	PRESSURE.
12.21 P.M.	$29\frac{1}{2}$ lbs.	12.27 P.M.	41 lbs.	12.32 P.M.	50 lbs., brace broke.
12.23 "	$33\frac{1}{2}$ "	12.29 "	$44\frac{1}{2}$ "	12.33 "	52 "
12.25 "	$37\frac{1}{2}$ "	12.31 "	$48\frac{1}{2}$ "	12.34 "	$53\frac{1}{2}$ " exploded.

In these second and third experiments we have illustrations of the comparatively rare cases in which explosions actually occur.

The second was a perfectly new construction, in which corrosion had not developed a point of great comparative weakness, and the edges yielding along the lines of riveting on all sides simultaneously and very equally, the two halves were completely separated, and thrown far apart with all of the energy of

unmistakable explosion, although there was an ample supply of water, and the pressure did not exceed that frequently reached in locomotives and on the western rivers, and although the boiler itself was quite diminutive.

In the third experiment as in the second it is probable that the weakest part extended very uniformly over a large part of the boiler, either in lines of weakened metal, or over surfaces largely acted upon by corrosion. Immediately upon the giving way of its braces, fracture took place at once in many different parts.

295. **Conclusions.**—We may conclude, then, from the result of Mr. Stevens' experiments:

First. That "low-water," although undoubtedly one cause, is not the only cause of violent explosions, as is so commonly supposed; but that a most violent explosion may occur with a boiler well supplied with water, and in which the steam-pressure is gradually and slowly accumulated.

This was shown on a small scale by the experiments of the committee of the Franklin Institute above referred to.

Second. That what is generally considered a moderate steam-pressure may produce the very violent explosion of a weak boiler, containing a large body of water, and having all its flues well covered.

This had never before been directly proven by experiment.

Third. That a steam-boiler may explode, under steam, at a pressure less than that which it had successfully withstood at the hydrostatic test.

The last boiler had been tested to 59 pounds, and afterward exploded at 53½ pounds. This fact, too, although frequently urged by some engineers, was generally disbelieved. It was here directly proven.*

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* A number of instances of this kind, though not always producing an explosion, have been made known to the Author. Two boilers at the Detroit Water Works, in 1859, after resisting the hydrostatic test of 200 pounds with water, at a temperature of 100° Fahr., broke several braces each at 110 and 115 pounds steam-pressure respectively, when first tried under steam. The boiler of the U. S. steamer Algonquin was tested with 150 pounds cold-water pressure, and broke a brace at 100 pounds when tried with steam. A similar case occurred in New York a few years ago, and the boiler exploded with fatal results. These acci-

In addition to the deductions summarized above, the Author would conclude—

Fourth. That the violence of an explosion under gradually accumulating pressures is determined largely by the nature of the injury and the extent of the primary rupture due to it. A merely local defect or failure would not be likely to cause explosion.

Fifth. That the overheating of the metal of a boiler in consequence of low-water may or may not produce explosion, accordingly as the sheet is more or less weakened or as the amount of steam made on the overflow of the dry heated area by water is greater or less.

Sixth. That the superheating of either water or steam is not to be considered a probable cause of explosions.

Seventh. That the question whether the repulsion of water from a plate by the overheating of the latter may occur with resulting explosion remains unsettled; but that it is certain that the number of explosions attributable to this cause is comparatively small.

Eighth. That all explosions are certainly due to simple and preventable causes, and nearly all to simple ignorance or carelessness, on the part of either designer, constructor, proprietor, or attendants.

A committee of the British House of Commons, after long study and careful investigation of this subject, made the following recommendations:

(*a*) That it be distinctly laid down by statute that the steam-user is responsible for the efficiency of his boilers and machinery, and for employing competent men to work them; (*b*) that, in the event of an explosion, the onus of proof of efficiency should rest on the steam-user; (*c*) that in order to raise *prima-facie* proof, it shall be sufficient to show that the boiler was at the time of the explosion under the management of the owner or user, or his servant, and such *prima-facie* proof shall only be rebutted by proof that the accident arose

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dents are probably caused by changes of form of the boiler, under varying temperature, which throw undue strain upon some one part, which may have already been nearly fractured.

from some cause beyond the control of such owner or user; and that it shall be no defence in an action by a servant against such owner or user being his master, that the damage arose from the negligence of a fellow-servant.

The Prevention of steam-boiler explosions is now seen to be a matter of the utmost simplicity. A well-designed, well-made and set, and properly managed steam-boiler may be considered as safe. Explosions never occur in such cases. To secure correct design and proportions, a competent engineer should be found to make the plans; to obtain good construction, a reliable, intelligent and experienced maker must be intrusted with the construction under proper supervision and precise instructions from the designer; and the latter should also attend carefully to the installation of the boiler. In order to insure good management, trustworthy, skilful, and experienced attendants must be found, who, under definite instructions, may at all times be depended upon to do their work properly. Periodical inspection, prompt repair of all defects when discovered, and the removal of the boiler before it has become generally deteriorated and unreliable are absolute safeguards against explosion.

APPENDIX.

TABLE I.—PROPERTIES OF SATURATED STEAM.

NOTE.—The following table gives the data required by the engineer in this connection as based upon the experiments of Regnault. The temperatures, pressures, and heat-measures are all from Regnault's experiments. The other quantities were calculated by Mr. R. H. Buel,* adopting the formulas of Rankine already given to obtain quantities not ascertained by direct experiment. The two parts of the latent heat of vaporization are separately determined, and the internal thus distinguished from the external work of expansion. British measures are adopted. The nomenclature is sufficiently well explained by the table-headings.

Pressure above a vacuum, in pounds per square inch.	Temperature, Fahrenheit degrees.	Quantities of Heat. In British Thermal Units. Required to raise the temperature of the water from 32° to $T°$.	Quantities of Heat. In British Thermal Units. Internal latent heat.	Quantities of Heat. In British Thermal Units. External latent heat.	Quantities of Heat. In British Thermal Units. Latent heat of evaporation at pressure $P = I + E$.	Quantities of Heat. In British Thermal Units. Total heat of evaporation above 32° $= S + L$.	Quantities of Heat. Total heat of evaporation above 32°, in units of evaporation.	Weight of a cubic foot of steam, in pounds.	Volume. Of a pound of steam in cubic feet.	Volume. Ratio of volume of steam to volume of equal weight of distilled water at temperature of maximum density.	Pressure above a vacuum, in pounds per square inch.
P	t	S	I	E	L	H	U	W	C	V	P
1	102.018	70.040	981.396	61.619	1043.015	1113.055	1.1522	.003027	330.4	20,623	1
2	126.302	94.368	961.980	64.114	1026.094	1120.462	1.1599	.005818	171.9	10,730	2
3	141.654	109.764	949.725	65.655	1015.380	1125.144	1.1647	.008522	117.3	7,325	3
4	153.122	121.271	940.597	66.773	1007.370	1128.641	1.1683	.011172	89.51	5,588	4
5	162.370	130.563	933.239	67.660	1000.899	1131.462	1.1712	.013781	72.56	4,530	5
6	170.173	138.401	927.038	68.403	995.441	1133.842	1.1737	.016357	61.14	3,816	6
7	176.945	145.213	921.654	69.041	990.695	1135.908	1.1758	.018908	52.89	3,302	7
8	182.952	151.255	916.883	69.602	986.485	1137.740	1.1777	.021436	46.65	2,912	8
9	188.357	156.699	912.584	70.106	982.690	1139.389	1.1794	.023944	41.77	2,607	9
10	193.284	161.660	908.672	70.560	979.232	1140.892	1.1810	.026437	37.83	2,361	10
11	197.814	166.225	905.083	70.967	976.050	1142.275	1.1824	.028911	34.59	2,159	11
12	202.012	170.457	901.766	71.332	973.098	1143.555	1.1837	.031376	31.87	1,990	12
13	205.929	174.402	898.683	71.663	970.346	1144.748	1.1849	.033828	29.56	1,845	13
14	209.604	178.112	895.784	71.973	967.757	1145.869	1.1861	.036265	27.58	1,721	14
14.69	212.000	180.531	893.894	72.175	966.069	1146.600	1.1869	.037928	26.37	1,646	14.69
15	213.067	181.608	893.044	72.274	965.318	1146.926	1.1872	.038688	25.85	1,614	15
16	216.347	184.919	890.458	72.549	963.007	1147.926	1.1882	.041109	24.33	1,519	16
17	219.452	188.056	888.007	72.811	960.818	1148.874	1.1892	.043519	22.98	1,434	17

* Weisbach's Mechanics, vol. ii., part ii., Dubois' translation. N. Y.: J. Wiley & Sons. 1884.

P	t	S	I	E	L	H	U	W	C	V	P
18	222.424	191.058	885.661	73.060	958.721	1149 779	1.1901	.045920	21.78	1.359	18
19	225.255	193.918	883.427	73.298	956.725	1150.643	1.1910	.048312	20.70	1,292	19
20	227.964	196.655	881.289	73.525	954.814	1151.469	1.1919	.050696	19.73	1,231	20
21	230.565	199.285	879 239	73.739	952.978	1152.269	1.1927	.053074	18.84	1,176	21
22	233.069	201.817	877.267	73.942	951.209	1153.026	1.1935	.055446	18.04	1,126	22
23	235.479	204.258	875 368	74.136	949.504	1154 762	1.1943	.057812	17.30	1,080	23
24	237.803	206.610	873.538	74.323	947.861	1155 471	1.1950	.060171	16.62	1,038	24
25	240.053	208.887	871.767	74.503	946.270	1155.157	1.1957	.062524	16.00	998.4	25
26	242.225	211.089	870.052	74.678	944 730	1155.819	1.1964	.064870	15.42	962.3	26
27	244.333	213.223	868.391	74.847	943.238	1156.461	1.1971	.067210	14.88	928.8	27
28	246.376	215.293	866.780	75.011	941 791	1157.084	1.1978	.069545	14.38	897.6	28
29	248.363	217.308	865.215	75.168	940.383	1157.691	1.1984	.071875	13.91	868.5	29
30	250.293	219.261	863.700	75.319	939.019	1158.280	1.1990	.074201	13.48	841.3	30
31	252.171	221.165	862.221	75.466	937.687	1158.852	1.1996	.076522	13 07	815.8	31
32	254.002	223 021	860.781	75.608	936.389	1159.410	1.2002	.078839	12.68	791.8	32
33	255.782	224.827	859.382	75.745	935.127	1159.954	1.2008	.081152	12.32	769.2	33
34	257.523	226 594	858.013	75.878	933.891	1160.485	1.2013	.083461	11.98	748.0	34
35	259 221	228.316	856.680	76.007	932.687	1161.003	1.2018	.085766	11.66	727.9	35
36	260.883	230.001	855.375	76.133	931.508	1161.509	1.2023	.088067	11.36	708.8	36
37	262.505	231.650	854.099	76.255	930.354	1162.004	1.2028	.090364	11.07	690.8	37
38	264.093	233.261	852.852	76.375	929.227	1162.488	1.2033	.092657	10.79	673.7	38
39	265.647	234.840	851.629	76 493	928.122	1162.962	1.2038	.094946	10.53	657.5	39
40	267.168	236.386	850.432	76.608	927.040	1163.426	1.2043	.097231	10.28	642.0	40
41	268.660	237.902	849.261	76.719	925.980	1163.882	1.2048	.099514	10.05	627.3	41
42	270 122	239.389	848.113	76.827	924.940	1164.329	1.2053	.101794	9.826	613.3	42
43	271.557	240.846	846.988	76 932	923.920	1164.766	1.2058	.104071	9.609	599.9	43
44	272.965	242.275	845 884	77.035	922.919	1165.194	1.2062	.106345	9.403	587.0	44
45	274.347	243.680	844.799	77.136	921.935	1165.615	1.2066	.108616	9.207	574.7	45
46	275.704	245.061	843.733	77.235	920.968	1166.029	1.2070	.110884	9.018	563.0	46
47	277.036	246.418	842.687	77.331	920.018	1166 436	1.2074	.113149	8.838	551.7	47
48	278.348	247.752	841.659	77.425	919.084	1166.836	1.2078	.115411	8 665	540.9	48
49	279.637	249 064	840.647	77.517	918.164	1167.228	1.2082	.117670	8.498	530.5	49
50	280.904	250.355	839.653	77.607	917.260	1167.615	1.2086	.119927	8.338	520 5	50
51	282.151	251.624	838.675	77.696	916 371	1167.995	1.2090	.122181	8.185	510.9	51
52	283.381	252.875	837.710	77.784	915.494	1168.369	1.2094	.124433	8.037	501.7	52
53	284.589	254.106	836.762	77.870	914.632	1168.738	1.2098	.126682	7.894	492.8	53
54	285.781	255.321	835.827	77.954	913.781	1169.102	1.2102	.128928	7.756	484.2	54
55	286.955	256.518	834.906	78 036	912.942	1169.460	1.2106	.131172	7.624	475.9	55
56	288.111	257.695	834.001	78.117	912.118	1169.813	1.2110	.133414	7.496	467.9	56
57	289.251	258.857	833.108	78.196	911.304	1170.161	1.2114	.135654	7.372	460.2	57

PROPERTIES OF SATURATED STEAM—(*Continued*).

Pressure above a vacuum, in pounds per square inch.	Temperature, Fahrenheit degrees.	Quantities of Heat. In British Thermal Units. Required to raise the temperature of the water from 32° to $T°$.	Internal latent heat.	External latent heat.	Latent heat of evaporation at pressure $P = I + E$.	Total heat of evaporation above 32° $= S + L$.	Total heat of evaporation above 32°, in units of evaporation.	Weight of a cubic foot of steam, in pounds.	Volume. Of a pound of steam in cubic feet.	Ratio of volume of steam to volume of equal weight of distilled water at temperature of maximum density.	Pressure above a vacuum, in pounds per square inch.
P	*t*	*S*	*I*	*E*	*L*	*H*	*U*	*W*	*C*	*V*	*P*
58	290.374	260.002	832.228	78.273	910.501	1170.503	1.2117	.137892	7.252	452.7	58
59	291.483	261.132	831.361	78.348	909.709	1170.841	1.2120	.140128	7.136	445.5	59
60	292.575	262.248	830.507	78.421	908.928	1171.176	1.2123	.142362	7.024	438.5	60
61	293.653	263.348	829.663	78.494	908.157	1171.505	1.2127	.144594	6.916	431.7	61
62	294.717	264.433	828.830	78.566	907.396	1171.829	1.2130	.146824	6.811	425.2	62
63	295.768	265.506	828.005	78.638	906.643	1172.149	1.2133	.149052	6.709	418.8	63
64	296.805	266.566	827.191	78.709	905.900	1172.466	1.2136	.151277	6.610	412.6	64
65	297.830	267.612	826.388	78.779	905.167	1172.779	1.2140	.153500	6.515	406.6	65
66	298.842	268.644	825.596	78.847	904.443	1173.087	1.2143	.155721	6.422	400.8	66
67	299.843	269.666	824.814	78.913	903.727	1173.393	1.2146	.157940	6.332	395.2	67
68	300.831	270.674	824.042	78.978	903.020	1173.694	1.2149	.160157	6.244	389.8	68
69	301.807	271.669	823.280	79.042	902.322	1173.991	1.2152	.162372	6.159	384.5	69
70	302.774	272.657	822.524	79.105	901.629	1174.286	1.2155	.164584	6.076	379.3	70
71	303.728	273.633	821.778	79.167	900.945	1174.578	1.2158	.166794	5.995	374.3	71
72	304.669	274.597	821.041	79.228	900.269	1174.866	1.2161	.169003	5.917	369.4	72
73	305.603	275.530	820.312	79.288	899.600	1175.150	1.2164	.171210	5.841	364.6	73
74	306.526	276.493	819.589	79.349	898.938	1175.431	1.2167	.173417	5.767	360.0	74
75	307.440	277.427	818.873	79.410	898.283	1175.710	1.2170	.175622	5.694	355.5	75
76	308.344	278.350	818.166	79.469	897.635	1175.985	1.2173	.177825	5.624	351.1	76

P	t	S	I	E	L	H	U	W	C	V	P
77	309.239	279.265	817.468	79.526	896.994	1176.259	1.2176	.180027	5.555	346.8	77
78	310.123	280.170	816.777	79.582	896.359	1176.529	1.2179	.182229	5.488	342.6	78
79	311.000	281.066	816.090	79.639	895.729	1176.795	1.2181	.184429	5.422	338.5	79
80	311.866	281.952	815.413	79.695	895.108	1177.060	1.2184	.186627	5.358	334.5	80
81	312.725	282.830	814.742	79.749	894.491	1177.321	1.2187	.188823	5.296	330.6	81
82	313.576	283.701	814.077	79.802	893.879	1177.580	1.2190	.191017	5.235	326.8	82
83	314.417	284.562	813.419	79.856	893.275	1177.837	1.2193	.193210	5.176	323.1	83
84	315.250	285.414	812.768	79.909	892.677	1178.091	1.2195	.195401	5.118	319.5	84
85	316.076	286.260	812.122	79.961	892.083	1178.343	1.2198	.197591	5.061	315.9	85
86	316.893	287.096	811.484	80.012	891.496	1178.592	1.2200	.199781	5.006	312.5	86
87	317.705	287.927	810.850	80.063	890.913	1178.840	1.2203	.201969	4.911	309.1	87
88	318.510	288.750	810.222	80.113	890.335	1179.085	1.2205	.204155	4.898	305.8	88
89	319.306	289.565	809.601	80.162	889.763	1179.328	1.2208	.206340	4.846	302.5	89
90	320.094	290.373	808.986	80.210	889.196	1179.569	1.2210	.208525	4.796	299.4	90
91	320.877	291.176	808.375	80.258	888.633	1179.809	1.2212	.210709	4.746	296.3	91
92	321.653	291.970	807.770	80.305	888.075	1180.045	1.2215	.212892	4.697	293.2	92
93	322.422	292.758	807.170	80.351	887.521	1180.279	1.2217	.215074	4.650	290.2	93
94	323.183	293.539	806.575	80.397	886.972	1180.511	1.2220	.217253	4.603	287.3	94
95	323.939	294.314	805.985	80.442	886.427	1180.741	1.2222	.219430	4.557	284.5	95
96	324.688	295.083	805.400	80.487	885.887	1180.970	1.2224	.221604	4.513	281.7	96
97	325.431	295.845	804.821	80.531	885.352	1181.197	1.2227	.223778	4.469	279.0	97
98	326.169	296.601	804.245	80.576	884.821	1181.422	1.2229	.225950	4.426	276.3	98
99	326.900	297.350	803.675	80.620	884.295	1181.645	1.2232	.228122	4.384	273.7	99
100	327.625	298.093	803.108	80.665	883.773	1181.866	1.2234	.230293	4.342	271.1	100
101	328.345	298.832	802.544	80.709	883.253	1182.085	1.2236	.232464	4.302	268.5	101
102	329.060	299.566	801.985	80.752	882.737	1182.303	1.2238	.234634	4.262	266.0	102
103	329.769	300.293	801.432	80.794	882.226	1182.519	1.2240	.236803	4.223	263.6	103
104	330.471	301.014	800.884	80.835	881.719	1182.733	1.2242	.238972	4.185	261.2	104
105	331.169	301.731	800.339	80.875	881.214	1182.945	1.2245	.241139	4.147	258.9	105
106	331.862	302.444	799.796	80.916	880.712	1183.156	1.2247	.243304	4.110	256.6	106
107	332.550	303.152	799.258	80.956	880.214	1183.366	1.2249	.245467	4.074	254.3	107
108	333.232	303.854	798.725	80.995	879.720	1183.574	1.2251	.247629	4.038	252.1	108
109	333.911	304.551	798.196	81.034	879.230	1183.781	1.2254	.249789	4.003	249.9	109
110	334.582	305.242	797.672	81.072	878.744	1183.986	1.2256	.251947	3.969	247.8	110
111	335.250	305.927	797.153	81.110	878.263	1184.190	1.2258	.254105	3.935	245.7	111
112	335.914	306.609	796.637	81.147	877.784	1184.393	1.2260	.256263	3.902	243.6	112
113	336.573	307.285	796.125	81.184	877.309	1184.594	1.2262	.258420	3.870	241.6	113
114	337.226	307.956	795.617	81.221	876.838	1184.794	1.2264	.260576	3.838	239.6	114
115	337.874	308.621	795.114	81.257	876.371	1184.992	1.2266	.262732	3.806	237.6	115
116	338.518	309.281	794.614	81.293	875.907	1185.188	1.2268	.264887	3.775	235.7	116
117	339.159	309.939	794.114	81.330	875.444	1185.383	1.2270	.267041	3.745	233.8	117

PROPERTIES OF SATURATED STEAM—(*Continued*).

Pressure above a vacuum, in pounds per square inch.	Temperature, Fahrenheit degrees.	Quantities of Heat. In British Thermal Units. Required to raise the temperature of the water from 32° to T°.	Internal latent heat.	External latent heat.	Latent heat of evaporation at pressure $P = I + E$.	Total heat of evaporation above 32° $= S + L$.	Total heat of evaporation above 32°, in units of evaporation.	Weight of a cubic foot of steam, in pounds.	Volume. Of a pound of steam in cubic feet.	Ratio of volume of steam to volume of equal weight of distilled water at temperature of maximum density.	Pressure above a vacuum, in pounds per square inch.
P	t	S	I	E	L	H	U	W	C	V	P
118	339.796	310.592	793.619	81.366	874.985	1185.577	1.2272	.269195	5.715	231.9	118
119	340.430	311.241	793.126	81.403	874.529	1185.770	1.2274	.271348	3.685	230.1	119
120	341.058	311.885	792.637	81.439	874.076	1185.961	1.2276	.273500	3.656	228.3	120
121	341.681	312.524	792.152	81.474	873.626	1186.150	1.2278	.275651	3.628	226.5	121
122	342.300	313.161	791.669	81.509	873.178	1186.339	1.2280	.277801	3.600	224.7	122
123	342.916	313.795	791.189	81.543	872.732	1186.527	1.2282	.279949	3.572	223.0	123
124	343.528	314.425	790.711	81.578	872.289	1186.714	1.2284	.282097	3.545	221.3	124
125	344.136	315.051	790.236	81.612	871.848	1186.899	1.2286	.284243	3.518	219.6	125
126	344.741	315.672	789.765	81.646	871.411	1187.083	1.2288	.286389	3.492	218.0	126
127	345.340	316.289	789.298	81.679	870.977	1187.266	1.2290	.288533	3.466	216.4	127
128	345.936	316.903	788.834	81.711	870.545	1187.448	1.2292	.290677	3.440	214.8	128
129	346.530	317.513	788.374	81.742	870.116	1187.029	1.2293	.292820	3.415	213.2	129
130	347.121	318.121	787.914	81.774	869.688	1187.809	1.2295	.294961	3.390	211.6	130
131	347.706	318.725	787.458	81.805	869.263	1187.988	1.2296	.297102	3.366	210.1	131
132	348.287	319.325	787.004	81.837	868.841	1188.166	1.2298	.299242	3.342	208.6	132
133	348.867	319.922	786.554	81.868	868.422	1188.344	1.2300	.301382	3.318	207.1	133
134	349.443	320.515	786.105	81.900	868.005	1188.520	1.2302	.303521	3.295	205.7	134
135	350.015	321.105	785.659	81.931	867.590	1188.695	1.2304	.305659	3.272	204.2	135
136	350.584	321.692	785.215	81.962	867.177	1188.869	1.2306	.307797	3.249	202.8	136
137	351.149	322.274	784.775	81.992	866.767	1189.041	1.2308	.309934	3.227	201.4	137
138	351.711	322.853	784.339	82.021	866.360	1189.213	1.2309	.312070	3.204	200.0	138

P	t	S	I	E	L	H	U	W	C	V	P
139	352.271	323.429	783.905	82.050	865.955	1189.384	1.2311	.314205	3.182	198.7	139
140	352.827	324.003	783.472	82.080	865.552	1189.555	1.2313	.316338	3.161	197.3	140
141	353.380	324.573	783.042	82.109	865.151	1189.724	1.2315	.318471	3.140	196.0	141
142	353.931	325.141	782.613	82.138	864.751	1189.892	1.2316	.320603	3.119	194.7	142
143	354.478	325.705	782.188	82.166	864.354	1190.059	1.2318	.322735	3.099	193.4	143
144	355.022	326.265	781.766	82.194	863.960	1190.225	1.2320	.324867	3.078	192.2	144
145	355.562	326.823	781.346	82.221	863.567	1190.390	1.2321	.326998	3.058	190.9	145
146	356.100	327.378	780.927	82.249	863.176	1190.554	1.2323	.329128	3.038	189.7	146
147	356.636	327.930	780.510	82.277	862.787	1190.717	1.2324	.331257	3.019	188.5	147
148	357.169	328.479	780.096	82.304	862.400	1190.879	1.2326	.333386	3.000	187.3	148
149	357.697	329.024	779.684	82.332	862.016	1191.040	1.2328	.335515	2.981	186.1	149
150	358.223	329.566	779.275	82.359	861.634	1191.200	1.2330	.337643	2.962	184.9	150
160	363.346	334.850	775.296	82.616	857.912	1192.762	1.2346	.358886	2.786	173.9	160
170	368.226	339.892	771.505	82.854	854.359	1194.251	1.2361	.380071	2.631	164.3	170
180	372.886	344.708	767.891	83.072	850.963	1195.671	1.2376	.401201	2.493	155.6	180
190	377.352	349.329	764.430	83.273	847.703	1197.032	1.2390	.422280	2.368	147.8	190
200	381.636	353.766	761.111	83.462	844.573	1198.339	1.2404	.443310	2.256	140.8	200
210	385.759	358.041	757.916	83.640	841.556	1199.597	1.2417	.464295	2.154	134.5	210
220	389.736	362.168	754.834	83.808	838.642	1200.810	1.2430	.485237	2.061	128.7	220
230	393.575	366.152	751.862	83.966	835.828	1201.980	1.2442	.506139	1.976	123.3	230
240	397.285	370.008	748.988	84.115	833.103	1203.111	1.2454	.527003	1.898	118.5	240
250	400.883	373.750	746.203	84.256	830.459	1204.209	1.2465	.547831	1.825	114.0	250
260	404.370	377.377	743.508	84.388	827.896	1205.273	1.2476	.568626	1.759	109.8	260
270	407.755	380.905	740.891	84.510	825.401	1206.306	1.2487	.589390	1.697	105.9	270
280	411.048	384.337	738.350	84.623	822.973	1207.310	1.2497	.610124	1.639	102.3	280
290	414.250	387.677	735.878	84.731	820.609	1208.286	1.2507	.630829	1.585	99.0	290
300	417.371	390.933	733.470	84.835	818.305	1209.238	1.2517	.651506	1.535	95.8	300
350	431.96	406.26	722.20	85.28	807.48	1213.74	1.256	.754534	1.325	82.7	350
400	444.92	419.76	712.34	85.60	797.94	1217.70	1.260	.857185	1.167	72.8	400
450	456.62	432.18	703.28	85.84	789.12	1221.30	1.264	.959536	1.042	65.1	450
500	467.42	443.52	695.01	86.01	781.02	1224.54	1.267	1.061700	.942	58.8	500
550	477.50	454.14	687.34	86.12	773.46	1227.60	1.270	1.16380	.859	53.6	550
600	486.86	464.22	680.08	86.18	766.26	1230.48	1.273	1.26586	.790	49.3	600
650	495.68	473.58	673.40	86.20	759.60	1233.18	1.276	1.36791	.731	45.6	650
700	504.14	482.40	667.11	86.19	753.30	1235.70	1.279	1.46995	.680	42.4	700
750	512.06	490.86	661.04	86.14	747.18	1238.04	1.282	1.57198	.636	39.6	750
800	519.62	498.88	665.34	86.08	741.42	1240.30	1.285	1.67401	.597	37.1	800
850	526.82	506.66	649.84	86.00	735.84	1242.50	1.287	1.77603	.563	34.9	850
900	533.66	514.03	644.71	85.91	730.62	1244.65	1.289	1.87804	.532	33.0	900
950	540.32	521.30	639.60	85.80	725.40	1246.70	1.291	1.98004	.505	31.4	950
1000	546.80	528.30	634.68	85.68	720.36	1248.66	1.293	2.08203	.480	30.0	1000

The column headed "*U*" in the table of the properties of saturated steam is useful for reducing the performance of different boilers to a common standard—this standard being that most generally accepted by engineers: the equivalent evaporation at atmospheric pressure and the temperature of boiling water, or, as it is frequently called, the evaporation from and at 212°. In the table it is assumed that the temperature of the feed-water is 32°, and an auxiliary table is added, giving corrections for any temperature of feed from 32° to 212°.

CORRECTION FOR TOTAL HEAT IN UNITS OF EVAPORATION.

Temperature of feed, Fahrenheit degrees.	Correction.	Temperature of feed, Fahrenheit degrees.	Correction.	Temperature of feed, Fahrenheit degrees.	Correction.	Temperature of feed, Fahrenheit degrees.	Correction.	Temperature of feed, Fahrenheit degrees.	Correction.
33	.0010	69	.0383	105	.0756	141	.1129	177	.1504
34	.0021	70	.0393	106	.0766	142	.1140	178	.1514
35	.0031	71	.0404	107	.0777	143	.1150	179	.1525
36	.0041	72	.0414	108	.0787	144	.1160	180	.1535
37	.0052	73	.0424	109	.0797	145	.1171	181	.1545
38	.0062	74	.0435	110	.0808	146	.1181	182	.1556
39	.0073	75	.0445	111	.0818	147	.1192	183	.1566
40	.0083	76	.0456	112	.0829	148	.1202	184	.1577
41	.0093	77	.0466	113	.0839	149	.1213	185	.1587
42	.0104	78	.0476	114	.0849	150	.1223	186	.1598
43	.0114	79	.0487	115	.0860	151	.1233	187	.1608
44	.0124	80	.0497	116	.0870	152	.1244	188	.1618
45	.0135	81	.0507	117	.0880	153	.1254	189	.1629
46	.0145	82	.0518	118	.0891	154	.1264	190	.1639
47	.0155	83	.0528	119	.0901	155	.1275	191	.1650
48	.0166	84	.0538	120	.0911	156	.1285	192	.1660
49	.0176	85	.0549	121	.0922	157	.1296	193	.1670
50	.0186	86	.0559	122	.0932	158	.1306	194	.1681
51	.0197	87	.0569	123	.0943	159	.1316	195	.1691
52	.0207	88	.0580	124	.0953	160	.1327	196	.1702
53	.0217	89	.0590	125	.0963	161	.1337	197	.1712
54	.0228	90	.0601	126	.0974	162	.1348	198	.1723
55	.0238	91	.0611	127	.0984	163	.1358	199	.1733
56	.0248	92	.0621	128	.0994	164	.1368	200	.1743
57	.0259	93	.0632	129	.1005	165	.1379	201	.1754
58	.0269	94	.0642	130	.1015	166	.1389	202	.1764
59	.0279	95	.0652	131	.1025	167	.1400	203	.1775
60	.0290	96	.0663	132	.1036	168	.1410	204	.1785
61	.0300	97	.0673	133	.1046	169	.1420	205	.1796
62	.0311	98	.0683	134	.1057	170	.1431	206	.1806
63	.0321	99	.0694	135	.1067	171	.1441	207	.1817
64	.0331	100	.0704	136	.1077	172	.1452	208	.1827
65	.0342	101	.0714	137	.1088	173	.1462	209	.1837
66	.0352	102	.0725	138	.1098	174	.1473	210	.1848
67	.0362	103	.0735	139	.1109	175	.1483	211	.1858
68	.0372	104	.0746	140	.1119	176	.1493	212	.1869

TABLE Ia.

TEMPERATURES AND PRESSURES, SATURATED STEAM.
IN METRIC MEASURES AND FROM REGNAULT.

Temperature	Steam-pressure. In Centimetres.	Steam-pressure. In Atmospheres	Temperature.	Steam-pressure. In Centimetres.	Steam-pressure. In Atmospheres
− 32° C.	0.0320	0.0004	+ 14° C.	1.1908	0.016
31	0.0352	0.0005	15	1.2699	0.017
30	0.0386	0.0005	16	1.3536	0.018
29	0.0424	0.0006	17	1.4421	0.019
28	0.0464	0.0006	18	1.5357	0.020
27	0.0508	0.0007	19	1.6346	0.022
26	0.0555	0.0007	20	1.7391	0.023
25	0.0605	0.0008	21	1.8495	0.024
24	0.0660	0.0009	22	1.9659	0.026
23	0.0719	0.0009	23	2.0888	0.028
22	0.0783	0.0010	24	2.2184	0.029
21	0.0853	0.0011	25	2.3550	0.031
20	0.0927	0.0012	26	2.4988	0.033
19	0.1008	0.0013	27	2.5505	0.034
18	0.1095	0.0014	28	2.8101	0.037
17	0.1189	0.0015	29	2.9782	0.039
16	0.1290	0.0017	30	3.1548	0.042
15	0.1400	0.0018	31	3.3406	0.044
14	0.1518	0.0020	32	3.5359	0.047
13	0.1646	0.0022	33	3.7411	0.049
12	0.1783	0.0024	34	3.9565	0.052
11	0.1933	0.0025	35	4.1827	0.055
10	0.2093	0.0027	36	4.4201	0.058
9	0.2267	0.0030	37	4.6691	0.061
8	0.2455	0.0032	38	4.9302	0.065
7	0.2658	0.0035	39	5.2039	0.068
6	0.2876	0.0038	40	5.4906	0.072
5	0.3113	0.0041	41	5.7910	0.076
4	0.3368	0.0044	42	6.1055	0.080
3	0.3644	0.0048	43	6.4346	0.085
2	0.3941	0.0052	44	6.7790	0.089
1	0.4263	0.0056	45	7.1391	0.094
0	0.4600	0.0061	46	7.5158	0.099
+ 1	0.4940	0.0065	47	7.9093	0.104
2	0.5302	0.0070	48	8.3204	0.109
3	0.5687	0.0073	49	8.7499	0.115
4	0.6097	0.0080	50	9.1982	0.121
5	0.6534	0.0086	51	9.6661	0.127
6	0.6998	0.0092	52	10.1543	0.134
7	0.7492	0.0199	53	10.6636	0.140
8	0.8017	0.0107	54	11.1945	0.147
9	0.8574	0.011	55	11.7478	0.155
10	0.9165	0.012	56	12.3244	0.163
11	0.9792	0.013	57	12.9251	0.170
12	1.0457	0.014	58	13.5505	0.178
13	1.1162	0.015	59	14.2015	0.187

TABLE Ia.—*Continued.*

Temperature.	Steam-pressure.		Temperature.	Steam-pressure.	
	In Centimetres.	In Atmospheres		In Centimetres.	In Atmospheres
+ 60° C.	14.8791	0.196	+110° C.	107.537	1.415
61	15.5839	0.205	111	111.209	1.463
62	16.3170	0.215	112	114.983	1.513
63	17.0791	0.225	113	118.861	1.564
64	17.8714	0.235	114	122.847	1.616
65	18.6945	0.246	115	126.941	1.670
66	19.5496	0.257	116	131.147	1.726
67	20.4376	0.267	117	135.466	1.782
68	21.3596	0.281	118	139.902	1.841
69	22.3165	0.294	119	144.455	1.901
70	23.3093	0.306	120	149.128	1.962
71	24.3393	0.320	121	153.925	2.025
72	25.4073	0.334	122	158.847	2.091
73	26.5147	0.349	123	163.896	2.157
74	27.6624	0.364	124	169.076	2.225
75	28.8517	0.380	125	174.388	2.295
76	30.0838	0.396	126	179.835	2.366
77	31.3600	0.414	127	185.420	2.430
78	32.6811	0.430	128	191.147	2.515
79	34.0488	0.448	129	197.015	2.592
80	35.4643	0.466	130	203.028	2.671
81	36.9287	0.486	131	209.194	2.753
82	38.4435	0.506	132	215.503	2.836
83	40.0101	0.526	133	221.969	2.921
84	41.6298	0.548	134	228.592	3.008
85	43.3041	0.570	135	235.373	3.097
86	45.0344	0.593	136	242.316	3.188
87	46.8221	0.616	137	249.423	3.282
88	48.6687	0.640	138	256.700	3.378
89	50.5759	0.665	139	264.144	3.476
90	52.5450	0.691	140	271.763	3.576
91	54.5778	0.719	141	279.557	3.678
92	56.6757	0.746	142	287.530	3.783
93	58.8406	0.774	143	295.686	3.890
94	61.0740	0.804	144	304.026	4.000
95	63.3778	0.834	145	312.555	4.113
96	65.7535	0.865	146	321.274	4.227
97	68.2029	0.897	147	330.187	4.344
98	70.7280	0.931	148	339.298	4.464
99	73.3305	0.965	149	348.609	4.587
100	76.000	1.000	150	358.123	4.712
101	76.7590	1.036	151	367.843	4.840
102	81.6010	1.074	152	377.774	4.971
103	84.5280	1.112	153	387.918	5.104
104	87.5410	1.152	154	398.277	5.240
105	90.6410	1.193	155	408.856	5.380
106	93.8310	1.235	156	419.659	5.522
107	97.1140	1.278	157	430.688	5.667
108	100 4910	1.322	158	441.945	5.815
109	103.965	1.368	159	453.436	5.966

TABLE I*a*.—*Continued.*

Temperature.	Steam-pressure.	
	In Centimetres.	In Atmospheres
+160° C.	465.162	6.120
161	477.128	6.278
162	489.336	6.439
163	501.791	6.603
164	514.497	6.770
165	527.454	6.940
166	540.669	7.114
167	554.143	7.291
168	567.882	7.472
169	581.890	7.656
170	596.166	7.844
171	610.719	8.036
172	625.548	8.231
173	640.660	8.430
174	656.055	8.632
175	671.743	8.839
176	687.722	9.049
177	703.997	9.263
178	720.572	9.481
179	737.452	9.703
180	754.639	9.929
181	772.137	10.150
182	789.952	10.394
183	808.084	10.633
184	826.540	10.876
185	845.323	11.123
186	864.435	11.374
187	883.882	11.630
188	903.668	11.885
189	923.795	12.155
190	944.270	12.425
191	965.093	12.699
192	986.271	12.977
193	1007.804	13.261
194	1029.701	13.549
195	1051.963	13.842
+196° C.	1074.595	14.139
197	1097.500	14.441
198	1120.982	14.749
199	1144.746	15.062
200	1168.896	15.380
201	1193.437	15.703
202	1218.369	16.031
203	1243.700	16.364
204	1269.430	16.703
205	1295.566	17.047
206	1322.112	17.396
207	1349.075	17.751
208	1376.453	18.111
209	1404.252	18.477
210	1432.480	18.848
211	1461.132	19.226
212	1490.222	19.608
213	1519.748	19.997
214	1549.717	20.391
215	1580.133	20.791
216	1610.994	21.197
217	1642.315	21.690
218	1674.090	22.027
219	1706.329	22.452
220	1739.036	22.882
221	1772.213	23.319
222	1805.864	23.761
223	1839.994	24.210
224	1874.607	24.666
225	1909.704	25.128
226	1945.292	25.596
227	1981.376	26.071
228	2017.961	26.552
229	2055.048	27.040
230	2092.640	27.535

TABLE II.

TOTAL AVAILABLE ENERGY IN WATER AND STEAM.

Pressure above a vacuum in pounds per square inch.	Same pressure as indicated by steam-gauge, allowing 14.7 pounds for atmospheric pressure.	Absolute pressure in atmospheres.	Number of British thermal units required for the evaporation of one pound of water, known as latent heat of evaporation, *H*.	Temperature in degrees Fahrenheit of the steam and of the water from which it is evaporated.	Temperature in degrees Centigrade of the steam and of the water from which it is evaporated.	Corresponding absolute temperature in degrees Fahrenheit.	Corresponding absolute temperature in degrees Centigrade.	Amount of energy contained in one pound of water which may be liberated by explosion or expansion to 212° Fahr.	Corresponding amount of energy contained in the latent heat of evaporation.	Total amount of energy contained in one pound of steam at corresponding temperatures and pressures.
20	5.3	1.36	954.415	227.9	108.8	689.0	382.8	145.9	16872.9	17018.8
25	10.3	1.70	945.825	240.0	115.5	701.2	389.5	439.7	29156.8	29596.5
30	15.3	2.04	938.925	250.2	121.2	711.4	395.2	813.5	38921.9	39735.4
35	20.3	2.38	932.1523	259.1	126.1	720.3	400.1	1223.4	47054.9	48278.3
40	25.3	2.72	926.4728	267.1	130.1	728.3	404.6	1645.7	54111.7	55757.4
45	30.3	3.06	921.3343	274.2	134.5	735.4	408.5	2112.9	60158.1	62271.0
50	35.3	3.40	916.6316	280.8	138.2	742.0	412.2	2550.4	65613.8	68164.2
55	40.3	3.74	912.2906	286.8	141.5	748.0	415.5	2999.9	70428.7	73428.6
60	45.3	4.08	908.2472	292.5	144.7	753.7	418.7	3449.2	74884.6	78333.8
65	50.3	4.42	904.4621	297.7	147.6	758.9	421.6	3899.8	78850.5	82750.3
70	55.3	4.76	900.8991	302.7	150.4	763.9	424.4	4361.1	82577.7	86938.8
75	60.3	5.10	897.5269	307.3	152.9	768.5	426.9	4815.8	85923.6	90739.4
80	65.3	5.44	894.3304	311.8	155.4	773.0	429.4	5206.5	89138.7	94345.2
85	70.3	5.78	891.2862	316.0	157.7	777.2	431.7	5638.9	92073.3	97712.2
90	75.3	6.12	888.3758	320.0	160.0	781.2	434.0	6058.1	94814.7	100872.8
95	80.3	6.46	885.5887	323.8	162.1	785.0	436.1	6474.2	97447.2	103921.4
100	85.3	6.80	882.9144	327.5	164.1	788.7	438.1	6885.2	99787.6	106672.8
105	90.3	7.14	880.3429	331.1	166.1	792.3	440.1	7290.3	102163.3	109453.6
110	95.3	7.48	877.8653	334.5	168.0	795.7	442.0	7689.0	104334.9	112023.9
115	100.3	7.82	875.4721	337.8	169.8	799.0	443.8	8087.3	106421.7	114509.0
120	105.3	8.16	873.1555	340.9	171.6	802.1	445.6	8483.1	108325.4	116808.5
125	110.3	8.50	870.9115	344.0	173.3	805.2	447.3	8864.9	110219.9	119084.8
130	115.3	8.84	868.7351	347.0	175.0	808.2	449.0	9252.6	112025.6	121278.2
135	120.3	9.18	866.6223	349.9	176.6	811.1	450.6	9627.0	113745.7	123372.7
140	125.3	9.52	864.5661	352.7	178.1	813.9	452.1	9992.6	115382.1	125374.7

TABLE II.—(*Continued*).

Pressure above a vacuum in pounds per square inch.	Same pressure as indicated by steam-gauge, allowing 14.7 pounds for atmospheric pressure.	Absolute pressure in atmospheres.	Number of British thermal units required for the evaporation of one pound of water, known as latent heat of evaporation, *H*.	Temperature in degrees Fahrenheit of the steam and of the water from which it is evaporated.	Temperature in degrees Centigrade of the steam and of the water from which it is evaporated.	Corresponding absolute temperature in degrees Fahrenheit.	Corresponding absolute temperature in degrees Centigrade.	Amount of energy contained in one pound of water which may be liberated by explosion or expansion to 212° Fahr.	Corresponding amount of energy contained in the latent heat of evaporation.	Total amount of energy contained in one pound of steam at corresponding temperatures and pressures.
145	130.3	9.86	862.5679	355.5	179.7	816.7	453.7	10361.0	117003.5	127364.5
150	135.3	10.20	860 6213	358.1	181.1	819.3	455.1	10536.5	118477.2	129003.7
155	140.3	10.54	858.7276	360 7	182.6	821.9	456.6	11085.9	119939.4	131025.3
160	145.3	10.88	856.8740	363.2	184.0	824.4	458.0	11444.2	121323.6	132767.8
165	150.3	11.22	855.0654	365.7	185.4	826.9	459.4	11823.4	122697.8	134521.2
170	155.3	11.56	853.2942	368.1	186.7	829.3	460.7	12141.3	123995.5	136136.8
175	160.3	11.90	851.5670	370.5	188.0	831.7	462.0	12508.7	125284.7	137793.4
180	165.3	12.24	849.8698	372.8	189.3	834.0	463.3	12821.4	126499.1	139320.5
185	170.3	12.58	848.2086	375.0	190.5	836.2	464.5	13182 0	127642.4	140824.4
190	175.3	12.92	846.5844	377.2	191.7	838.4	465.7	13367.1	128778.8	142145.9
195	180.3	13.26	844.9938	379.4	193.0	840.6	467.0	13844.1	129908.3	143752.4
200	185.3	13.60	843.4326	381.5	194.1	842.7	468.1	14153.3	130967.4	145120.7
210	195.3	14.28	840.3967	385.6	196.4	846.8	470.4	14830.8	133003.2	147834.0
220	205.3	14.66	838.5864	389.8	198.7	851.0	472.7	15463.1	136003.3	151466.4
230	215.3	15.64	833.9691	394.2	201.2	855.4	475.2	16180.3	137134.2	153314.7
240	225.3	16.32	832.6419	397.9	203.3	859.1	477.3	16790.2	139094.3	155884.5
250	235.3	17.00	830.3630	401.0	205.0	862.2	479.0	17314.4	140516.0	157830.4
500	485.3	34.01	780.8592	467.6	242 0	898.8	516.0	30055.5	165892.7	195948.2
1000	985.3	68.02	720.4350	546.8	286.0	1008.0	560.0	48671.5	179212.0	227883.5
2000	1985.3	136.05	643.9049	643.7	339.8	1104.9	613.8	75777.2	194221.3	269998.5
3000	2985.3	204.08	590.8038	708.3	375.7	1169.5	649.7	96116.3	193555.0	289671.3
4000	3985.3	272.10	544.6774	763.7	405.9	1223.9	679.9	114498.6	189201.7	303700.3
5000	4985.3	340.13	505.7339	807.8	431.0	1269 0	705.1	130494.2	183305.9	313800 1
6000	5985.3	408.16	471.8473	845.9	452.1	1307.1	726.1	144413.4	176656.9	321070.3
7000	6985.3	486.19	439.9985	881.2	471.7	1342.4	745.7	157944.2	169333.3	327277.5
8000	7985.3	544.21	409.4533	914.3	490.1	1375.5	764.1	170832.0	161392.6	332224.6
9000	8985.3	612.24	382.6347	945.2	507.3	1406.4	781.5	183998.6	153998.0	337142.6
10000	9985.3	680.27	355.2491	971.4	521.8	1432.6	795.8	193787.0	145376.8	339164.2
100000	99985.3	6802.72	305.3040	2163.4	1184.1	2624.6	1458.1	....	....	... ...

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